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The determination of the orientation of section planes of meteoritic irons.

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THE Widmanstetter figures on a general plane section of a meteoritic iron of the octahedrite class consist of kamacite bands running in four directions, the traces of the four planes of the octahedron, while tessellated octahedrites show three more sets of bands, the traces of the cube planes. The angles which these bands make with one another give data which are in principle sufficient to define the crystallographic axes of the iron, but in practice there does not appear to be any simple direct method of effecting this definition. In the following, two simpler cases are first discussed, followed by a method for the general case somewhat shorter than any published method[1] I am aware of, and by methods for orientation from the Neumann lines and from inclusions.

Mass with two non-parallel etched surfaces.[2]

If the iron has two etched surfaces meeting in an edge, it will in general be possible to measure the orientation of the kamacite bands on both

[1] A. Brezina, 1881; F. Becke, 1886; A. Himmelbauer, 1909; N. T. Belaiew, 1923; J. Leonhardt, 1928; C. S. Barrett, 1937. For references see list on p. 165.

[2] The methods described in this section had been previously used by the author for the construction of a crystal projection from drawings or photographs of the crystal from two (or more) directions making a known angle with one another. N. T. Belaiew (1923), R. F. Mehl and C. S. Barrett (1931), and D. W. Smith (1933) describe the use of two etched surfaces at right angles to locate the poles of inclusions or twin-planes, using the stereographic projection. C. S. Barrett (1937) outlines a method for the orientation of a plane from its traces on two etched surfaces which need not be at right angles, using the cyclographic projection (wrongly styled stereographic) and a Wulff net. Belaiew appears to have been the first to make full use of two etched surfaces, though Brezina and others used a second surface to eliminate ambiguities.

surfaces relative to this edge and the angle between the two etched surfaces; and by inspection of the edge, with a lens if necessary, it can be seen which pairs of bands on the two surfaces arise from the same kamacite plate. From these data it is a very simple matter to construct graphically a projection showing the relation of the two etched surfaces to the crystallographic axes, and if there is more than one crystal present, to determine their relative orientation. Two slightly different constructions are needed according as the angle between the two etched surfaces is between about 70° and 110° or outside these limits.

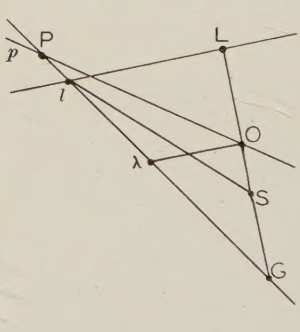

Fig. 1.

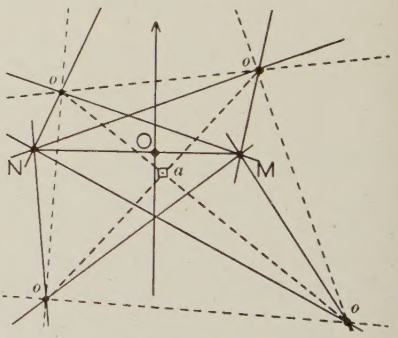

Fig. 2.

Fig. 1. Location of the gnomonic pole of a crystal plane from the traces of the plane on two surfaces at a known angle to one another, in projection on one of the two surfaces. Radius of projection 1·5 cm.

Fig. 2. Determination of the orientation of the left-hand crystal, *A*, of the Gibeon mass (B.M. 1941,1) from the traces of the octahedral planes on two etched faces, *M* and *N*. Gnomonic projection with radius 1·5 cm., on a plane in zone with the two etched surfaces. One of the cube poles is marked *a*, and the six cubo-octahedral zones are dotted.

If the angle is relatively small, one of the two etched surfaces is conveniently taken as plane of projection with centre *O* (fig. 1); on this plane are plotted the linear (*Ll*), gnomonic (*G*), and stereographic (*S*) projections of the other etched surface; the line *Ll* is parallel to the edge between the two surfaces. Now if *P* is the gnomonic projection[1] of any crystal plane, the line *OP* is normal to the trace of that plane on the plane of projection; hence a line *Op* through *O* making the same angle with *GSO* as the trace of *P* on the plane of projection does with the edge between the two etched surfaces must contain the pole *P*. Again, the

[1] The constructions are somewhat simpler in linear projection (see below, fig. 9), but the unfamiliarity of that projection probably outweighs the simpler constructions.

direction of the trace of P on the second etched surface can be found by the Goldschmidt (1891) construction for drawing crystals from the gnomonic projection; reversing this, if we draw a line through S making the same angle with GSO as the trace of P on the second etched surface does with the edge between the two surfaces and cutting the line Ll in l and join Gl, then Gl also must contain the pole P. Thus the gnomonic pole P is located by the intersection of Op and Gl.

Having located the poles of the octahedral planes, these are joined in pairs by straight lines, the other three intersections of which are the poles of the cube planes; the orientation of the etched surfaces in the crystal is fully defined by this projection and any angles desired may readily be measured, or if desired a new projection on any convenient plane may be prepared in the usual way. Unlike the two methods described below for the orientation of a mass with a single etched surface, this method always gives quite unambiguous results so long as the traces on the two etched surfaces can be paired off with certainty.

If the angle between the etched surfaces is too near 90° (between about 70° and 110°) the pole G will be so far from the centre as to make the above graphical construction impracticable. But if a projection plane is chosen in any position having a convenient known relation to the two etched surfaces, the reversed Goldschmidt construction can be applied twice. If the selected plane of projection is in zone with the two etched surfaces, as in fig. 2, the linear projections of the two etched surfaces will be parallel to one another and to the gnomonic projection of the edge between them; a knowledge of the direction of this edge is essential to the construction, forming the link between the measured angles on the two surfaces. If the selected plane of projection is not in zone with the two etched surfaces, the gnomonic projection E_G of the edge between the etched surfaces will be the line GG' (fig. 9 G), and its linear projection the point E_L where the linear projections L and L' of the two etched surfaces cut; now if GG' cuts the linear projections L and L' in g and g', the lines Sg, $S'g'$ replace GSO as the reference directions from which the lines Sl, $S'l'$ are set out at the observed angles; should g or g' lie unduly far from the centre, the directions of Sg, $S'g'$ may still be found readily, since they are at right angles to SE_L, $S'E_L$.

As an alternative to the selection of a different plane of projection when either L or G is unduly distant from the centre, the necessary distances and angles may be calculated: $\tan OGl / \tan OSl = LS/LG = \cos GO$; $Ll = R.\operatorname{cosec} GO.\tan OSl$ (where R is the radius of projection); a line normal to GSO cuts Gl in λ, $O\lambda = R.\sin GO.\tan OSl$; and

$LlG = O\lambda G = 90° - OGl$ (fig. 1). It will almost always be possible to draw in Gl from a suitable selection of these angles, but should some particular line lie unduly distant from O, recourse must be had to the stereographic or the linear projection.

Two difficulties may arise in the application of this method. It may not be possible to make certain which set of traces on one etched surface corresponds to any particular set on the other etched surface; in this case we have four lines through O and four through G (fig. 1), and do not know how to pair them off. They can be paired off in 24 different ways, and it is necessary to find by trial which of these ways represents the projection of the octahedron planes of a cubic crystal. The gnomonic projection of an octahedron on a general plane is best recognized by joining all the faces in pairs; the six zone lines required meet in three additional points which, if the original four poles belong to a regular octahedron, will be the poles of the cube (a, figs. 2, 3); it is easy to test whether they are at 90° to one another. The difficulty may also be met by preparing a third etched face, in a known position relative to the first two; the three sets of lines now resulting will in general have only four, or at most ten, points of triple intersection; the selection of an octahedron from these will never be difficult.[1] This procedure is exemplified in fig. 3, which shows the orientation of a mass of the Butler iron from data for three etched surfaces given by A. Brezina (1881); the results agree well with Brezina's; one of the poles in fig. 3 lies too far from the centre for convenient gnomonic projection and has been treated stereographically. Secondly, it may not be convenient to prepare two etched surfaces which actually cut one another; yet it is absolutely necessary for the application of the method that the directions of the traces on both surfaces should be measured with respect to the line of intersection of the surfaces. This may readily be met by a variety of mechanical devices, of which the simplest is a pair of plates hinged together, each having an edge parallel to the axis of the hinge; if the plates are applied to the two etched surfaces, these two edges will both be parallel to the line of intersection of the surfaces, and reference marks can readily be made on both surfaces.

The above method has been applied to a mass of the Gibeon meteorite shower (B.M. 1941,1) described by Dr. L. J. Spencer (1941), which consists of two crystals with an irregular junction. On two etched surfaces at 84° to one another, the traces of the octahedron planes of one crystal

[1] This use of a third plane was proposed by R. F. Mehl and C. S. Barrett (1931) but never actually applied.

A (the left-hand one in fig. 11, pl. II of Dr. Spencer's paper) are inclined at the following angles,[1] measured clockwise from [*MN*], the intersection of the etched surfaces: on surface *M* (the surface shown in the figure), 22°, 62°, 98°, and 135°; and for the same octahedron planes on

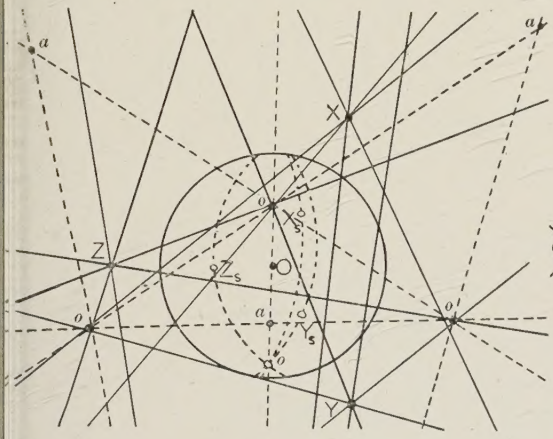

FIG. 3.

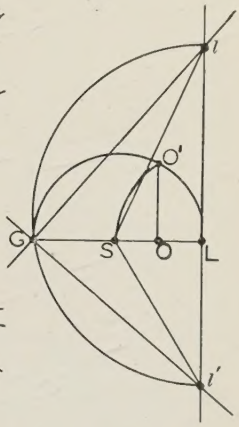

FIG. 4.

FIG. 3. An example of orientation from the directions of the traces on three etched surfaces (*X*, *Y*, *Z*): the Butler mass measured and figured by A. Brezina (1881). Mixed gnomono-stereographic projection, radius 1·5 cm.; stereographic poles shown as open circles. The six cubo-octahedral zones are dotted.

FIG. 4. Construction for determining the orientation of a cubic crystal from the traces of the cube faces on one reference face. Gnomonic projection, radius 1·0 cm.

surface *N* (which lies to the left in Dr. Spencer's figure, the edge [*MN*] being nearly parallel to the side of the figure), 106°, 38°, 150°, and 86° respectively. The second crystal, *B*, is only represented on surface *N* by a very small area, and it was not possible to measure all the traces accurately on this surface, nor to be sure of their correspondence with the traces on the surface *M*. On surface *M*, this second crystal shows seven traces, kamacite plates presumably parallel to the three planes of the cube being also present. The traces on surface *M* are inclined to the reference edge[2] at 7°, 28°, 56°, 88°, 122°, 135°, and 177° (measured clockwise), the 7°, 88°, and 177° traces probably being due to cube planes (the

[1] Taking the 135° trace as standard, Dr. L. J. Spencer's measurements (1941) place the other traces at 21°, 62°, and 98° to [*MN*].

[2] Taking the 135° trace as standard, Dr. L. J. Spencer's measurements (1941) place the other octahedron traces at 29°, 55°, and 124°, and the extra lamellae at 6°, 91°, and 176° to [*MN*].

7° trace is represented by a single kamacite plate); on surface *N*, there are traces at 44° and at roughly 85°, 115°, and 140° (these three angles are only very approximate); these appear to correspond with the 56°, 135°, 28°, and 122° traces on *M*, but owing to the small area of the surface it was not possible to be sure of this except for the first, nor even to be certain that the last three are octahedron and not cube traces.

Since one set of kamacite plates of the first crystal, *A*, gives traces at 135° and 86° on the two etched surfaces, and traces at about the same angles are observed in the areas occupied by the second crystal, though their common origin cannot be observed in this case, it appeared fairly probable that the two crystals had an octahedron face in common and were very possibly in twin position about [111].

No difficulty arose in locating the octahedron poles of the first crystal; a projection plane in the zone [*MN*], making an angle of 47° with *N* and 37° with *M*, was selected and the reversed Goldschmidt construction applied twice; the results are shown in fig. 2. The graphically determined poles are at angles of 67°, 73°, 69°, 71°, 74°, and 72° to one another, a reasonably good approach to the octahedral angle 70° 32′, and the poles of the two etched faces are located as follows: *M* at 82° to the octahedron pole *o* located by the 135° and 86° traces, in a zone at 19° clockwise to the zone [*oa*] (fig. 7), and *N* at 44° to the same pole *o*, in a zone at 69° anticlockwise to [*oa*]. This position gives calculated angles for the traces of crystal *A* on *M* of 23°, 63°, 97°, and 132°, and on *N* of 108°, 38°, 148°, and 87°, in good agreement with the observed values.

Since the correspondence of the traces of the second crystal, *B*, on the two etched surfaces (and indeed their positions on the surface *N*) is very uncertain, it seemed desirable to examine the 24 possible correspondences; only one (the one suggested by the observations and given above) gave poles roughly approximating to an octahedron, and this solution places the two crystals in roughly subparallel position, crystal *B* having an octahedron plane parallel to that plane of crystal *A* defined by the 135° and 86° traces on the two surfaces *M* and *N*, and being rotated about 10° relatively to crystal *A* about an axis normal to this common plane.

But owing to the difficulty of determining the positions of the traces of the planes of crystal *B* on the surface *N*, this result cannot be regarded as proven. However, we have reliable measurements of the positions of six of the seven traces of crystal *B* on the surface *M*, and any three of these should theoretically suffice to define the position of the crystal axes relative to the surface. There are four useful methods of procedure: by

a graphical construction, the traces of the three cube planes may be used to define the crystal axes; or the traces of the four octahedron planes may be used by trial and error (C. S. Barrett, 1937), or by a semi-graphical method described below; or the angles between the traces of the octahedron planes may be calculated for all positions of the etched surface relative to the crystal axes, and a set of theoretical angles in reasonable agreement with the observed ones selected. This last method has been used by A. Brezina (1881), N. T. Belaiew (1923), J. Leonhardt (1928), and A. Himmelbauer (1909), but it is not particularly convenient.

Further, if the two crystals are in twin position (about a [111] axis) the second can only be in one of four positions relative to the first, and since the orientation of crystal *A* has been established without ambiguity, it is a simple matter to test whether any of the four possible twin relations gives traces at the angles observed. This has been done, but in none of the four possible twin positions do the graphically calculated positions of the traces agree with the observations.

Tessellated octahedrite with a single etched surface.

If the traces of the three cube planes on a reference surface are measurable, as they may be in a tessellated octahedrite, it is possible to determine the orientation of the crystal relative to the surface by a direct graphical construction. For suppose a gnomonic projection made on a cube face (fig. 4), and let *O* be the centre of projection, and *Ll* the linear, *G* the gnomonic, and *S* the stereographic projection of the etched surface; then the directions of the traces of the cube on the etched surface are normal to *SO*, *Sl*, and *Sl′*, where *l* and *l′* are found by drawing lines through *G* parallel to the two cube axes that lie in the plane of the projection to cut *Ll* in *l* and *l′*. To reverse this construction, we begin with a projection on a cube face, of unknown origin and radius of projection; with any convenient distance *SL*, draw *SL*, *Sl*, *Sl′* normal to the traces of the three cube faces, selecting *SL* so that it makes acute angles with both *Sl* and *Sl′*, while the angle *lSl′* is obtuse, and let *lLl′* be at right angles to *SL*; on *ll′* erect a semicircle, cutting *LS* produced in *G*; then *Gl* and *Gl′* are the directions of the two cube axes in the plane of projection. The origin and radius of projection are determined by erecting a semicircle on *LG* and striking an arc with centre *L* and radius *LS*, cutting the semicircle in *O′*; if *O′O* is made normal to *LS*, *O* is the origin and *OO′* the radius of projection, defining the position of the third cube axis relative to the reference surface. There is, however, one ambiguity; it is obvious that a turn through 180° about an axis normal to the etched surface will

not alter the directions of the traces, and accordingly this method (or any other using a single etched surface) always leads to a pair of solutions which have this relation to one another.

This procedure was applied to the Gibeon mass (B.M. 1941,1), taking the three traces on M at 7°, 88°, and 177° given by crystal B as cube planes. The construction located the cube axes at about 46°, 44°, and 85° to the pole of the etched surface, the last lying nearly in the surface at a small angle to the edge between the two surfaces; this position, however, leads to angles for the traces of the octahedron poles of 36°, 89°, 93°, and 146° clockwise from $[MN]$, in very poor agreement with observation, nor does any nearby position give better agreement, and there is reason to believe that the single kamacite lamella at 7° to the edge between the two etched surfaces does not represent a cube plane.

Octahedron traces on a single etched surface.

I have not been able to find a direct graphical solution for the orientation of a meteorite from the traces of the octahedron planes on a single etched surface, but the following procedure gives a solution by trial with a single variable. Trial with a single variable has several advantages over two-variable tables or over trial and error procedure with a Wulff net and a standard projection on tracing-paper (C. S. Barrett, 1931), giving greater certainty that no possible solution has been overlooked and allowing of interpolation with ease.

Let a gnomonic projection be prepared on one of the octahedron planes, and let O (fig. 5) be the centre of projection and pole of one octahedron plane, Ll the linear, S the stereographic, and G the gnomonic projections of the etched surface (position unknown); the gnomonic poles of the other three octahedron planes will lie 120° apart on a circle about O, of 70½° radius, which is drawn; GSO will be normal to the direction of one of the octahedron traces. Applying the reversed Goldschmidt construction, lines are drawn through S at the appropriate measured angles made by the other three traces with the one selected as GSO, to cut Ll in three points, l, l', l''; then if the position of the etched surface in the projection was correctly chosen the gnomonic poles of the other three octahedron planes must lie at the intersections of Gl, Gl', Gl'' with the 70½° circle about O. It is a simple matter to carry out trials with values of GO at suitable intervals from 0 to 90°; any value of GO which leads to a sheaf of three lines Gl, Gl', Gl'' intersecting the 70½° circle at intervals of 120° is a possible solution and completes the orientation by locating the other octahedron poles with reference to GSO. There is,

however, one ambiguity, for since a turn through 180° about the normal to the etched surface does not alter the directions of the traces, each solution obtained from the above construction will define two orientations of the crystal relative to the etched surface, having this relation to one another.

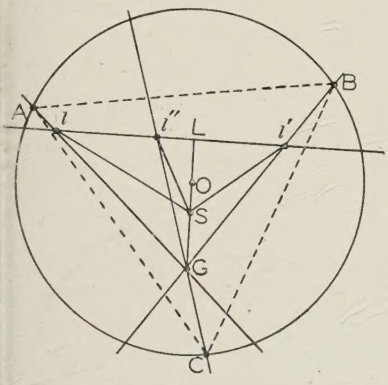

Fig. 5.

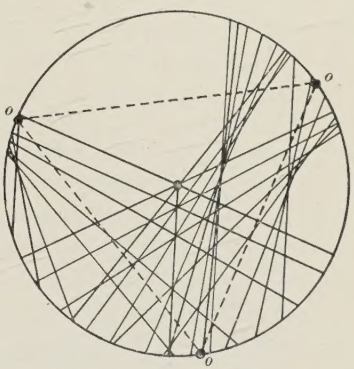

Fig. 6.

Fig. 5. Derivation of the directions of the octahedral traces on any section plane; gnomonic projection on an octahedron plane. Radius of projection 0·8 cm.

Fig. 6. Determination of the orientation of the section plane from the traces of the octahedron planes on one etched surface; this figure refers to the right-hand part of the Laurens County mass described by Himmelbauer. Gnomonic projection with radius 0·8 cm.

In practice, certain small modifications are necessary, for when GO is near 0°, Ll will be inconveniently distant from O; and when GO is near 90°, G will be inconveniently distant. But the angles OSl, OSl', OSl'' are the measured inter-trace angles, and $LS = R.\text{cosec } GO$, and $LG = R(\cot GO + \tan GO) = LS.\sec GO$ (where R is the radius of projection). Hence $\tan OGl = \tan OSl.\cos GO$, and $Ll = R.\text{cosec } GO.\tan OSl$. A table is therefore prepared of the angles OGl corresponding to the observed angles OSl and GO values at suitable intervals from 0° to 90°; the calculations may be carried out for 5° intervals in a few minutes, using a slide-rule, as $\frac{1}{2}$° accuracy is quite adequate; values of Ll' are also calculated for GO values above 75°. It is now possible to dispense with the graphical construction of Gl, and to draw in the lines Gl, Gl', Gl'' directly from the tabulated angles for all values of GO up to 75°; for GO values above 75°, the appropriate lines Ll are drawn, the proper distances Ll measured off, and the lines Gl drawn in at angles $LlG = 90° - OGl$. The lines Gl will be found to form three families (fig. 6), each

sweeping across the $70\frac{1}{2}°$ circle, and with the aid of a piece of thin celluloid or thick cellophane marked with three lines radiating at 120° and pivoted on a pin through *O*, all possible solutions are readily located.

There is only one complication; the angles *OSl* are measured angles, subject to errors of measurement, and hence the intersections of *Gl* with the $70\frac{1}{2}°$ circle will not lie at exactly 120° from each other even for the true position of *G*; and the departure may sometimes be quite considerable with unfavourable values of *OSl* and *GO*. It is therefore desirable to select that trace the direction of which can be most accurately measured as *GSO*, and whenever two only of the lines *Gl*, *Gl'*, *Gl''* intersect the $70\frac{1}{2}°$ circle at 120° to each other, to check whether the third 120° position leads to an inter-trace angle in fair agreement with observation. Experience with the method has led to some useful practical points; traces at small angles to the reference trace *GO* serve well to define the orientation of the triangle *ABC* relative to *GO*, but are apt to give uncertain values of *GO*, while traces at angles near 90° to *GO* define well the angle *GO*, but are apt to leave the orientation of the triangle imperfect. It is therefore often best to rely on the trace making the smallest angle with *GO* to define the orientation of the triangle *ABC* relative to *GO*, and take the mean of the *GO* values obtained from the three traces (other than *GO*) taken in pairs. Again, planes lying very near the section plane give no traces, or very broad ones of uncertain direction which would not be selected as *GO*; accordingly any solution giving a small value of the angle *GO*, or attributing an observed trace to a plane very near the section plane may be rejected unless the trace so attributed has the proper characters.

Where the etched surface shows only a single individual, the possible orientations may readily be described in terms of angles measured on the octahedral plane projection (figs. 5 and 6); but where two or more individuals are present, it will be preferable to change the projection plane so that the several individuals are all projected on the same plane; the etched surface will often serve as a convenient common projection plane. This transformation may be carried out without difficulty by the usual methods, either in gnomonic projection or after transformation to the stereographic. The reference line to which the measurements for the several individuals are referred is marked in, and all possible relative orientations of the individuals can be described without danger of error. Spinel-twinning will be obvious, even on such a chance plane of projection, since two crystals in twin position must have one face and the three cubo-octahedron zones through this face in common.

This method also has been applied to the Gibeon mass (B.M. 1941,1). The traces of the first (left-hand) crystal, A, on the first section plane M were taken as a test of the method; the octahedron plane giving rise to the 135° trace was selected as projection plane. The other three octahedron traces form angles with $[MN]$ of 22°, 62°, and 98° (clockwise). Using the above construction, no three poles at 120° could be found, but several pairs of poles at 120° could be located; the only possible solution being with GO 77°, when the 62° and 98° traces give poles at 120° and the third trace should be at 27° (observed 22°). This solution places the pole of M at 77° from the pole o of the octahedron giving rise to the 135° trace, in a zone 24° clockwise from $[oa]$ (fig. 7) and defines two positions of the crystal relative to the surface M, related by a turn through 180° about the normal M. One of these two positions brings the pole of N 133° from the pole of o in a zone 89° anticlockwise from $[oa]$ and gives calculated positions for the octahedron traces on N of 38°, 70°, 124°, 144° (observed, 38°, 86°, 106°, 150°); this position can accordingly be rejected. The other approximates to that found by consideration of both etched faces, for which the angles were M 83° from o and 19° clockwise from $[oa]$; it would place the pole of N at 44° from o in a zone 72° anticlockwise from $[oa]$ and give practically the same angles for the traces on N; the only difference between these last two positions is that one puts the error mainly on the 62° trace, the other mainly on the 22° trace, and any intermediate position would be equally acceptable.

Turning to the right-hand individual, B, the traces on M were treated by the above method, using the octahedron plane responsible for the 135° trace as projection plane. Again, no set of three poles at or very near 120° could be found, and the method used in the last paragraph was adopted; three possible solutions resulted, two of which are practically the same and were accordingly averaged, giving two solutions: the pole of M may be 77° from the octahedron plane o giving the 135° trace, in a zone at 7° clockwise from $[oa]$ (solution P), or it may be 35° from o in a zone 3° clockwise from $[oa]$ (solution Q). Each solution has two variants (P_1, P_2; Q_1, Q_2), related by a turn through 180° about the normal to M, which may be defined by reference to the pole of N: for P_1, N lies at 44° from o in a zone 89° anticlockwise from $[oa]$; for P_2, these angles are 132° and 105°; for Q_1, 60° and 125°; and for Q_2, 109° and 131°. Further study shows that positions P_1 and Q_2 are not very different from one another; but the difference is definite, and any intermediate position would give much worse agreement between the observed and calculated directions of the traces; positions P_2 and Q_1 are similarly related. If the

cube traces or the traces on the etched surface N were better developed for this crystal, it would be possible to decide between these solutions; on the whole, position P_1 for crystal B gives the best agreement, but P_2 is nearly as good, Q_2 is fair, and Q_1 cannot be wholly excluded.

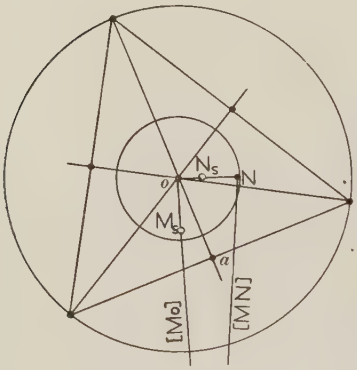

Fig. 7.

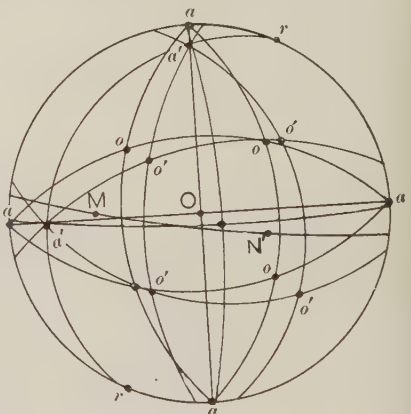

Fig. 8.

Fig. 7. The orientation of the left-hand crystal A, of the Gibeon mass (B.M. 1941, 1) with reference to the two etched surfaces M and N (M is the figured surface); in gnomonic projection on an octahedron plane. Radius of projection 0·8 cm.; the gnomonic pole of M falls outside the figure, so the stereographic pole is shown instead (M_s); the stereographic pole of N (N_s) is also shown.

Fig. 8. The relative positions of the two crystals of the Gibeon mass (B.M. 1941, 1) shown in stereographic projection on a cube face of the left-hand crystal, A. Radius of projection 2·5 cm. Pole of the rotation relating the two crystals marked r.

Elimination of ambiguities; true orientation of the Gibeon mass.

It has always been recognized that any method of orientation using only the directions of the traces on a single etched surface will necessarily give at least two solutions, related by a rotation of 180° around the normal to the etched surface, and may give more than one such pair. The means available for the elimination of these ambiguities were described by A. Brezina (1881): (1) subsidiary etched surfaces will normally prove very effective, but may fail if they are too small, while if they yield accurate measurements, these are best used by the first of the methods described above rather than as mere check values; (2) the approximate directions of one or more planes may be disclosed by natural features of the meteorite—weathering or cleavage cracks—and may prove sufficient; (3) in a deeply etched meteorite, the taenite plates may stand up sufficiently to give an oriented sheen which will decide their direction of

inclination to the etched surface, but care must be taken that the origin of such a sheen is fully established;[1] (4) Brezina observed the frequent occurrence of pits of sufficient dimensions to furnish approximate goniometric measurements on sealing-wax imprints, but this appears to have been due to the methods of section cutting and etching in use, as such pits do not appear on modern sections; (5) since the apparent width of any kamacite band is t cosec θ, where t is its true thickness and θ its angle of inclination to the etched surface, the mean relative widths of the several sets of bands serves as a rough measure of their several inclinations and may decide between pairs of solutions.

The application of these methods to crystal B of the Gibeon mass (B.M. 1941,1) shows that solution P_1 is the correct orientation. For with solutions P the 122° trace is at 33°, and the 135° trace at 77° to the surface M, while with solutions Q these angles become 75° and 35° respectively (the difference between the angles for the other traces is too small to be of any use); hence the 122° trace should be 1·8 times the width of the 135° trace with solutions P but only 0·6 of the width with solutions Q; it is readily seen from Dr. Spencer's figure (1941) that the 122° trace is the wider, so the pair of solutions Q may be rejected. Reflections from the projecting taenite plates give a sheen at positions which indicate that the 122° and 135° traces are respectively due to plates the normals to which emerge towards the top right and the bottom left corners of Dr. Spencer's figure; this accords with solution P_1 (P_2 would require the reverse).

The correctness of this solution was subsequently proved by the preparation and examination of a third etched surface. This third surface N' is exactly parallel to N, and is to the right of Dr. Spencer's figure; it cuts crystal B only, and shows traces at 128°, 43°, 147°, and 74°, measured anticlockwise[2] from the edge $[MN']$, and corresponding respectively with the 28°, 56°, 122°, and 135° traces on M; this agrees with the directions predicted for position P_1. It also allows of a direct solution

[1] In very deeply etched sections the taenite plates may project sufficiently to give fair goniometric reflections (cf. R. F. Mehl and C. S. Barrett, 1931). Besides this oriented sheen, arising from projecting taenite, there is another arising from the etched surface of the kamacite, and originating from planes near the cube planes of the kamacite (O.B. Bøggild, 1927); since the possible positions of the kamacite cube planes relative to the octahedron planes of the taenite are known, this should provide an approximate orientation of the latter and serve to eliminate ambiguities; but its application for this purpose would be troublesome.

[2] Since N' is opposite to N, angles measured anticlockwise on N' correspond in direction to those measured clockwise on N. No cube traces could be found on the surface N'.

for both crystals by the first method described above and as this is the most accurate method, it has been used; the results show that the planes of the two crystals giving rise to the 135° trace on surface M are not so nearly parallel as was at first thought, the angle between them being about 9°; for crystal B, the pole of M lies 75° from o in a zone at 7° clockwise to $[oa]$, and 47° from N in a zone at 90° to $[oa]$, a solution agreeing closely with solution P_1 above. The two crystals are related to one another by a rotation of 15° about an axis lying in a cube face, and inclined 27° to the normal to that cube face which in crystal B gives rise to the 88° traces (fig. 8); the rotation is clockwise in passing from A to B.

The single kamacite plate in crystal B visible on surface M at 7° to the edge $[MN]$ cannot be accounted for as an octahedron or a cube plane; its trace on M is a zone line having indices near [7.8.38], which suggests that it is probably really $(1\bar{1}0)$, which would give a trace at 11° to $[MN]$; but since it does not cross the edge $[MN]$ its orientation cannot be definitely established.

The relative orientation of the crystals in polycrystalline meteoritic irons.

In view of the rarity of iron meteorites showing more than one large crystal in a mass, and of the fact that three such masses have been described as spinel-twins, it would be of interest to carry out a survey of iron meteorites to determine the nature of the association wherever more than one crystal is present. At the moment, the British Museum collections are dispersed for safety and not available for such a survey, but it is hoped to make one in due course. As a preliminary, the data available from the literature have been studied and the evidence that the three masses described are spinel-twins checked. In each case, the available data consisted of trace directions on a single etched face; at best, this will give a pair of solutions for each crystal, four results in all for the orientation of the two crystals in the mass, but only two for their orientation with respect to one another. If one of these two possible relative orientations is a twin position, it is very probably the correct one for otherwise a chance section plane must have cut a pair of crystals in chance relative orientation to give the same angles as if it had cut a twin —a very improbable event. In the following, the statement that a reported twin has been confirmed must (unless amplified) be read as indicating that re-examination of the available data leads to a pair of possible relative orientations one of which is a twin position; without further evidence, it is possible, though not probable, that the relation may be only a chance one.

The $1\frac{1}{2}$-kg. mass of the Laurens County fall in the Vienna collection was described by A. Himmelbauer (1909) as a spinel-twin, with a well-developed composition-plane. A re-examination of his data confirmed the twin relation he found; he states that the orientation was checked from small additional etched faces, but gives no details.

A 72 cm. square plate of the Gibeon (Bethany) shower in the Vienna collection was described by F. Berwerth (1902) and by Himmelbauer (1909) as a spinel-twin with irregular composition surface. Re-examination of their data indicated that this finding is probably correct, but another pair of positions for the right-hand crystal are possible and would not be in twin relation to the left half. Again, Himmelbauer states that the orientation was checked from additional etched faces, but gives no details.

Another mass of the Gibeon shower, the 178-kg. Mukerop mass, was cut into two masses of 86 and 61 kg. and a slice of 16 kg.; this slice, in the Stuttgart collection, was described as a spinel-twin with well-developed composition-plane and figured by A. Brezina and E. Cohen (1902); the 61-kg. piece in the Vienna collection was described by A. Himmelbauer (1909), and this piece and several slices into which J. Böhm had cut the 86-kg. piece were described by F. Berwerth (1902), the 61-kg. piece being figured (evidently the opposed face to that figured by Brezina and Cohen). The positions found by these authors are in agreement and are confirmed by re-examination of their data. The several slices of this mass described by Berwerth show that several crystals are present; all save one are in repeated twin relation about one axis, some with well-developed composition-planes, some with irregular junctions. But one individual does not belong to this series; unfortunately, Berwerth gives no numerical data, and his sketch figures are too small for more than rough measurements, even if they may be assumed angularly accurate. However, the trace directions to be expected for a crystal twinned on any [111]-axis to a crystal in either of the orientations of the repeated twin series have been determined, and none of the six possibilities agrees even roughly with Berwerth's sketch; it is therefore almost certain that this crystal (Berwerth's no. 6) is not in twin relation to any of the others. It is desirable that one or more of the slices in which this individual is present should be re-examined and its orientation definitely established; the specimen B.M. 85891, weighing 4320 grams, was bought from J. Böhm in May 1902 and may be suitable; it is hoped to examine it when it is again accessible for study.

Thus the scanty data at present available show that the crystals in the crystalline iron meteorites may be in twin orientation about [111],

either with an irregular junction or with (111) as composition-plane; or they may be in roughly subparallel position; and it is probable that quite irregular relative positions also occur. It is noteworthy that three of the four polycrystalline masses so far described belong to the Gibeon shower.

Use of projections other than the gnomonic.

In all the above constructions the gnomonic projection has been used almost exclusively. But precisely parallel constructions may be made in the other three crystallographically useful projections.

In the stereographic projection the Goldschmidt construction for crystal drawing is paralleled by F. Stöber's (1899), which may be reversed in just the same way—a series of great circles are constructed through the stereographic pole of the etched surface at the same angles to the projection of the reference direction as the several traces make; the poles of the planes giving rise to the traces must lie on these great circles. This construction (fig. 9 S) may be preferred by some, but unless a very large radius of projection is used (a step which has several disadvantages), I find it uncomfortably cramped; and for the orientation of an octahedrite from traces on a single etched surface, the multiplicity of circles becomes far more confusing than the families of straight lines obtained in the gnomonic projection. The stereographic projection was used by C. S. Barrett and co-workers (1931–37) for the orientation of a plane from its traces on two etched surfaces, using a Wulff net to lay out the necessary angles, and for the orientation of a plane from its traces on a single etched surface by trial and error with two variables.

The reversed Goldschmidt construction is readily adapted to the linear projection,[1] (fig. 9 L), but on the balance this has no particular advantages over the gnomonic projection except perhaps for the orientation of an octahedrite from the traces on a single etched surface. Here the replacement of an assemblage of lines by points may reduce the chance of confusion and outweigh the unfamiliarity of the projection; the appropriate distances LT along various trial positions of the section plane L are conveniently calculated from the equation $LT = R.\sec LO.\cot \theta$, where θ is the angle between the reference trace L (which in this projection lies at infinity) and the trace T of an octahedron plane on the etched surface; an example of the use of this projection is shown in fig. 11.

[1] See E. S. Fedorov, 1898, for the adaptation of the direct Goldschmidt construction to these projections.

In the cyclographic projection, the reversed Goldschmidt construction is again readily paralleled, but it is doubtful if the projection has enough advantages to outweigh its unfamiliarity. It has, however, been proposed by C. S. Barrett (1937) to orient a mass with two non-parallel etched surfaces.

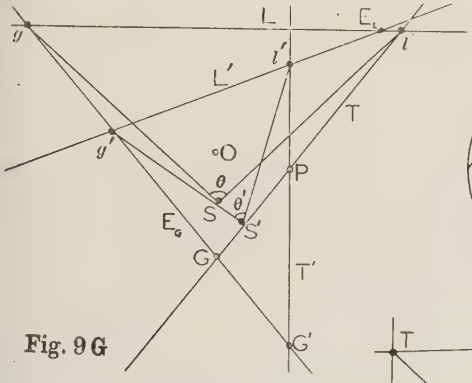

Fig. 9 G

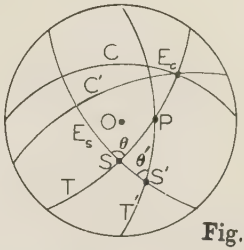

Fig. 9 S

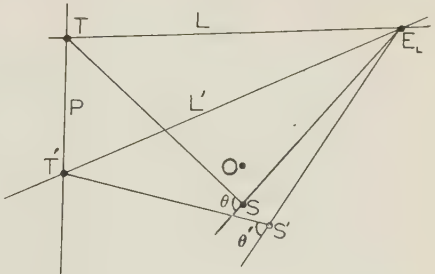

Fig. 9 L

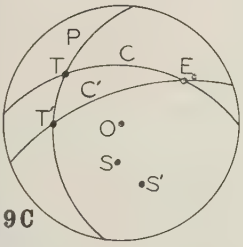

Fig. 9 C

Fig. 9. The location of a face pole or trace from the directions of the traces of the face on two planes; constructions in the four crystallographic projections: *G*, gnomonic; *S*, stereographic; *L*, linear; *C*, cyclographic (the same letters are used for the gnomonic, &c. projections of the two section planes in each figure). *P*, pole or trace of the required face; θ, θ', the angles between the traces of the required face in the two section planes and the edge *E* in which they meet; *T*, *T'*, zone-lines or poles of the traces of *P* on the two section planes. Radius of projection 1·5 cm. The same angles are used in all four projections.

A combination of the gnomonic and stereographic projections was advocated for general crystallography by T. V. Barker (1922), those poles which are too distant from the centre for convenient gnomonic projection being treated stereographically, and the combination is very effective and trouble-free for the present purpose also. The same end could be attained by a combination of the gnomonic and linear projections, but the risk of confusion is greater when two straight-line projec-

tions are combined (unless different colours of ink are used for the two) than in the combined gnomono-stereographic projection, where it is obvious which zone-lines belong to which projection. An example of this combined projection is given in fig. 3.

Orientation of a meteorite from Neumann lines.

The above methods should allow of the orientation of any octahedrite (except perhaps a small section of a coarsest octahedrite); the Neumann lines should in principle allow of the orientation of any mass in which they are well developed, and attention was next directed to the problem of their utilization. Where two or more etched surfaces are available, the method described on p. 141 should lead directly to an unambiguous orientation, and is greatly to be preferred wherever possible.

But it may be desirable to orient a mass from the Neumann lines on a single etched surface; while the following methods may be rather tedious and may lead to several possible solutions, they have proved effective in practice. C. S. Barrett (1937) proposes to use a method of trial and error with a Wulff net and a 'standard projection' of (211) on tracing-paper; he does not give any practical illustration, and it is very doubtful if all possible solutions could be traced in this way except at an inordinate expense in time.

A well-marked line, the direction of which can be accurately established, is selected as reference direction on the etched surface, and the corresponding (211) plane as plane of projection; as in the method described on p. 148 values of *OGl* and *Ll* (fig. 1), or if the linear projection is to be used values of *LT* (fig. 9 L), are calculated for values of *GO* at 5° or 10° intervals from 0 to 90° for each of the other Neumann lines observed.

It is quite possible to seek out all possible solutions by trial and error, using a gnomonic projection of the form (211) on one of its faces, made on transparent material,[1] as a trial plate over a gnomonic projection showing as families of lines the observed Neumann lines projected for various values of the angle *GO* between the face of (211) chosen as projection plane and the etched surface; the procedure is much the same as for the orientation from the Widmanstetter figures on a single etched surface. But if the directions of the observed Neumann lines are numerous the families of lines tend to become confusing, while the gnomonic projection of the form (211) on one of its faces, including as it

[1] A drawing made on thin typing-paper may be rendered reasonably transparent by painting it on both sides with a suitable colourless lacquer; a solution of vinyl acetate polymer serves very well.

does four poles at 80° 24′ from the centre, is inconveniently large. For these reasons, the linear projection is decidedly preferable for this particular problem.

In the linear projection, the sheaf of lines *Gl* through the pole *G* of the section plane are replaced by points *T* on the linear trace *Ll* of the plane. For the orientation of a meteorite from the observed Neumann lines a drawing is made on tracing-paper of the linear projections of a series of trial section planes at angles from 15° to 90° to the plane of projection, marking in on each the points *T* corresponding to the observed angles between the Neumann lines, one of which serves as reference direction, and its generating (211) plane as plane of projection; the points *T* are joined to give the loci of the linear projections of the several Neumann lines for all values of *GO*. This projection is laid over a linear projection of the cubic form (211) on one of its faces, and rotated about a pin through the centre of both; if any relative position can be found in which all the points *T* on one trial section plane fall on lines in the projection of the form (211), that relative position and section plane define a possible solution. The possibility that the section plane will lie within 15° of the plane of projection is very small, for a slip-plane within 15° of the etched surface is not likely to give a well-marked set of Neumann lines on that surface; but if it is felt desirable, another pair of projections with half the normal radius of projection (a 5 cm. radius is suitable for most of the above constructions) will reduce the unexamined range to $7\frac{1}{2}$°. In order that the trial projection on tracing-paper shall be kept to a reasonable size, the Neumann line selected as reference direction should be so chosen that it does not make a small angle with any other—if possible, not less than 20°, or better 30°. Allowance must be made for possible experimental error in the angles between the Neumann lines; loci drawn parallel to the loci of *T* at a distance equal to the estimated possible experimental error assist in this.

This method was tried for the orientation of the kamacite of the Pieladé do Bagre meteorite, a medium octahedrite with well-developed Neumann lines, described and figured by Dr. L. J. Spencer (1930). In Dr. Spencer's fig. 8, pl. XII, the directions of the Neumann lines in several lamellae can readily be measured; four of the best were selected for study, and fig. 10 serves as a key for the identification of these in his figure. The boundary between lamella *D* and the adjacent plessite triangle was taken as reference direction, and the following angles are measured clockwise: lamella *A* belongs to a family at 112° to lamella *D*, and has Neumann lines at 18°, 35°, 106°, and 141°; lamellae *B* and *C*, also

at 112° to D, have Neumann lines at 18°, 35°, 67°, 83°, 118°, and 151°; lamella D has Neumann lines at 12°, 18°, 41°, 93°, 136°, and 148°; and lamella E, at 45° to D, has Neumann lines at 89°, 103°, 132°, and 166°. The fourth, broad set of kamacite bands are not represented in Dr. Spencer's fig. 8, but according to his measurements they are at about 88° to D, and their generating plane is inclined about 20° to the etched surface.

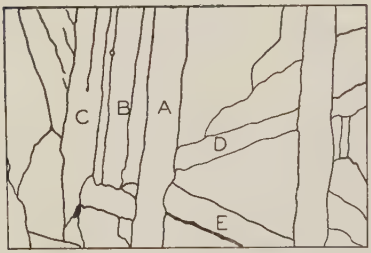

Fig. 10.

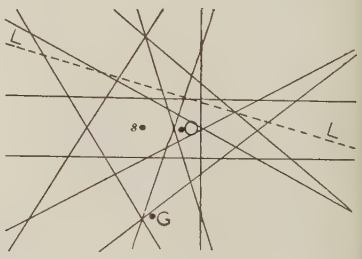

Fig. 11.

Fig. 10. Key to the kamacite lamellae selected for orientation by their Neumann lines from those shown in Min. Mag., vol. 22, pl. XII, fig. 8; medium octahedrite, Piedade do Bagre, Brazil. Scale ½ that of the plate.

Fig. 11. Orientation of a kamacite lamella (B) of the Piedade do Bagre meteorite from the Neumann lines; linear projection on a face of (211); six pairs of solutions agree with the observed directions of the lines; the one shown is the true solution. G, gnomonic pole and L linear projection of the etched surface; s, linear pole of [100]. Radius of projection 0·8 cm.

When studied by the above method, allowing each measurement an accuracy of ±3°, six pairs of solutions were obtained for the orientation of lamellae B and C; one of these is shown in linear projection on a face of the form (211) in fig. 11. For lamella D, eight pairs of solutions, and for A, forty-six pairs were obtained; lamella E was not studied. The immediate result of this work was to show that the method is a practical one, allowing of the orientation of the kamacite lattice from the Neumann lines on a single etched surface; the number of solutions obtained depends on the number of sets of Neumann lines observed and the accuracy with which their directions can be measured, and the present example is a particularly unfavourable one; at the same time, the results emphasize the desirability of using two etched surfaces where possible.

In many cases, a choice among the results obtained by the above method should be possible by utilizing the oriented sheen of the kamacite. As shown by O. B. Bøggild (1927) and by S. W. J. Smith, A. A. Dee,

and J. Young (1928),[1] this sheen on a surface etched with nitric acid is due to planes vicinal to (100); the sheen thus serves to locate approximately one or more cube planes. In the present instance, the specimen is temporarily inaccessible, and this help was not available.

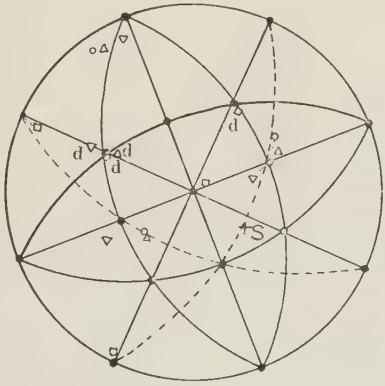

FIG. 12.

FIG. 12. The Piedade do Bagre meteorite; stereographic projection on a cube plane of the taenite, showing the stereographic pole, *S*, of the etched surface, and the orientation of several kamacite lamellae relative to the taenite. The poles of the taenite are shown as filled circles, of lamellae *B* and *C* (fig. 10) as open circles, of lamella *D* as squares, and of two possible positions of lamella *A* as upright and inverted triangles. The poles plotted are the cube poles of both kamacite and taenite, [111] and [110] of taenite, and that (110) pole, *d*, of each kamacite lamella which is normal to the Widmanstetter plane. The traces of the Widmanstetter planes are dotted.

The relative orientation of the kamacite and taenite.

The relative orientation of the kamacite and taenite in meteorites, and of the α- and γ-phases in artificial nickel-iron alloys and in plain carbon steels has been the subject of many studies. O.B. Bøggild (1927) used the oriented sheen and the included rhabdites as a means of orientation, while other authors have used X-ray methods.[2] While there are some differences of opinion as to the exact relative position of the two lattices, it is generally agreed that a (110) plane of kamacite is parallel to a (111) plane of taenite and to a plane of the Widmanstetter structure within

[1] Here it is also shown that when copper ammonium chloride is used for etching, the etch pits are bounded mainly by planes of (110).

[2] J. Young, 1926, 1930; G. Kurdjumow and G. Sachs, 1930; R. F. Mehl and S. V. Smith, 1934; Z. Nishiyama, 1934; R. F. Mehl and G. Derge, 1937; G. Derge and A. R. Kommel, 1937; S. W. J. Smith and J. Young, 1939; J. Young, 1939.

about 1°, while a [100] axis of the kamacite lying in the Widmanstetter plane is approximately parallel to a [110] axis of the taenite.

The orientation now obtained from the Neumann lines, while not approaching in accuracy that obtained by X-ray methods, provides independent confirmation of the truth of this approximate relative orientation: for of the six pairs of solutions obtained for lamellae *B* and *C*, only one shows any approach to a regular orientation, and this one has the (110) plane of the kamacite at about 3° to (111) of the taenite and a [100] axis of the kamacite about 13° from a [110] axis of the taenite in the Widmanstetter plane; of the eight pairs of solutions obtained for lamella *D*, the only one showing any approach to regular orientation has (110) of kamacite at 4° to (111) of taenite and a [100] axis of the kamacite about 6° from a [110] axis of the taenite in the Widmanstetter plane; and of the forty-six pairs of solutions obtained for lamella *A*, the Widmanstetter plane (111) of the taenite, coincides approximately with (111) of kamacite in three, with (211) in two, with (221) in three, with (210) in four, and with (110) in five pairs, while if the parallelism of (110) of kamacite with (111) of taenite be accepted, two of the ten solutions (five pairs) which fulfil this condition have a further regularity, namely an approximate coincidence of [100] kamacite with [110] taenite, the angles being 9° and 11° in the two cases. For lamellae *B*, *C*, and *D*, the confirmation of the accepted relative orientation of the kamacite and taenite is very satisfactory, while in the very unfavourable case of lamella *A* there is good agreement with the accepted orientation, but the data are not adequate to afford independent proof. The relative orientations of the taenite and these lamellae are shown, in projection on a cube plane of the taenite, in fig. 12.

The orientation of the tesseral lamellae of the Gibeon masses.

The orientation of the kamacite plates of typical octahedrites has thus been determined by both X-ray and purely morphological methods, with good agreement. But the orientation of those kamacite lamellae parallel to the cube plane of the taenite, which appear in the tessellated octahedrites, remains undetermined. J. Young (1939, p. 418) notes that it would appear possible that they might be oriented with one cube face of the kamacite and taenite parallel to one another and to the surface of the lamella, and a pair of dodecahedron planes of the kamacite parallel to the other two cube planes of the taenite; but from a study of F. Rinne's figures (1910) he considers it more probable that the kamacite in the tesseral plates has the normal orientation relative to the taenite.

The Gibeon mass (B.M. 1941,1) has been carefully examined and Young's suggestion is fully confirmed, for each tesseral plate studied was clearly seen to be continuous with one set of octahedral plates; the octahedral plates grow out from the tesseral plate in many places, and under suitable magnification, Neumann lines are visible, and can be seen to be parallel in a tesseral lamella and the set of octahedral lamellae having the same orientation. Referring to pl. II, fig. 11, of Dr. Spencer's paper (1941), the prominent double plate running vertically near the centre of the photograph consists of two plates in different orientations, the right-hand one being continuous with the octahedral lamellae at 28° to [*MN*], the left-hand one with those at 135°. Other lamellae have been examined with similar results. The single 7° lamella, possibly parallel to a face of (110), is of similar character and appears to be continuous with the octahedral lamellae at 56°.

The orientation of a meteoritic iron with the aid of inclusions.

Iron meteorites commonly carry inclusions of many kinds, some of which occur as rounded, featureless globules, while others form plates or needles in regular orientation relative to the matrix.[1] Where the relation

[1] O. B. Bøggild (1927) has shown that acicular rhabdites (schreibersite) in nickel-poor ataxites and octahedrites consist of square (tetragonal) prisms with their axes parallel to the [001] axes of the kamacite and their prism faces parallel to two faces of (210); Bøggild and also W. Borchert and J. Ehlers (1934) have shown that platy rhabdites (also schreibersite) are parallel to (221) and (100) of the kamacite. Brezina lamellae are large schreibersite plates parallel to (110) of taenite in octahedrites (A. Brezina, 1904), and cut across the octahedral structure. Shepard lamellae are thickish schreibersite plates enclosed in kamacite and arranged parallel to the Widmanstetter structure (J. D. Buddhue, 1938); it is not certain whether the kamacite swathing them has the normal orientation or not; if it has, the plates are parallel to (110) of kamacite. Curiously enough, R. F. Mehl, C. S. Barrett, and H. S. Jerabek (1934) have shown that platy inclusions of Fe_3P in manufactured iron do not follow any of these laws, but lie in a set of 24 planes near (310) of the iron; they also found that inclusions of Fe_4N form plates parallel to (210) of the iron. F. Heide, E. Herschkowitsch, and E. Preuss (1932) described the platy rhabdites of the Tocopilla (= Cerros del Buey Muerto) mass as parallel to faces of (100) (210), and (211) of the kamacite, but their proof is not satisfactory, and Borchert and Ehlers later showed that (100) and (221) are the true segregation planes. G. F. Kunz and E. Weinschenk (1892) described the platy rhabdites of the Indian Valley mass as parallel to the Neumann lines (and hence to (211) of kamacite); this requires confirmation. Troilite commonly occurs as rounded globules, but also as Reichenbach lamellae parallel to the cube planes of the taenite (G. Tschermak, 1872) or rarely to the dodecahedral planes of the taenite (F. Rinne, 1910). Plates of cohenite are commonly parallel to the Widmanstetter structure. Daubreelite is usually associated, often regularly, with troilite.

between inclusions and matrix is known, the above methods could obviously be applied to orient the matrix from the observed directions of the inclusions, preferably by using two etched surfaces; suitable material for a practical test is not at present available.

The orientation of the included phase relative to the matrix in segregate structures in general.

One of the commonest problems in dealing with segregate structures in general is to determine the orientation of the segregate with respect to the matrix.[1] The procedure most commonly used has been to determine the orientation of the matrix by X-ray methods, then to measure the directions of the traces of the inclusions on one or more etched surfaces and seek by trial and error a set of planes in the matrix capable of accounting for the observed traces.

This procedure employs more experimental data than are really necessary; the traces of the inclusions on two etched surfaces could be used by the above methods to determine the directions of the inclusions without difficulty, and once a projection has been obtained, the indexing of the segregation planes is simple. In theory the traces on a single etched surface are more than sufficient; the matter has been shortly dealt with by C. S. Barrett (1937), but without practical examples, and there is no evidence that any worker has succeeded in determining the orientation of the section planes of the inclusions in the matrix solely from the traces on a single etched surface except where the inclusions lie in the planes of the octahedron, dodecahedron, or cube. While the indexing of the planes of segregation in the matrix should normally be possible, the complete description of the orientation of the segregate with respect to the matrix will rarely be feasible from morphological data; for it requires recognizable structural features in the segregate, idiomorphic boundary planes, or the traces of cleavage or glide planes or inclusions in the segregate, which will rarely be available.

Summary.

Methods are described for determining the orientation of a plane section of a meteoritic iron from the Widmanstetter figures, the Neumann lines, or from oriented inclusions. The determination of the planes occupied by oriented phases in segregate structures in general is also

[1] O. B. Bøggild (1927) has used the acicular rhabdites to orient meteorites; his method was to etch rather deeply and then measure on the goniometer the positions of the prism faces of the rhabdites exposed by etching.

considered, and it is shown how this may often be attained without knowledge of the orientation of the section plane relative to the matrix. These methods have been applied to the determination of the relative orientation of the crystals in iron meteorites containing a few large crystals and to the determination of the relative orientation of kamacite and taenite in meteoritic irons.

References.

1872 G. Tschermak, Denkschr. Math.-naturwiss. Cl. Akad. Wiss. Wien, vol. 31, p. 192.
1881 A. Brezina, Denkschr. Math.-naturwiss. Cl. Akad. Wiss. Wien, vol. 44, p. 121.
1886 F. Becke, Tschermaks Min. Petr. Mitt., vol. 7, p. 93.
1891 V. Goldschmidt, Zeits. Kryst. Min., vol. 22, p. 41.
1892 G. F. Kunz and E. Weinschenk, Amer. Journ. Sci., ser. 3, vol. 43, p. 424.
1898 E. S. Fedorov, Zeits. Kryst. Min., vol. 30, p. 9.
1899 F. Stöber, Bull. Soc. Franç. Min., vol. 22, p. 42.
1902 F. Berwerth, Sitzungsber. Akad. Wiss. Wien, Math.-naturwiss. Cl., vol. 111, Abt. I, p. 646.
—— A. Brezina and E. Cohen, Jahresheft Ver. vaterl. Naturkunde Württemberg, vol. 58, p. 292.
1904 A. Brezina, Sitzungsber. Akad. Wiss. Wien, Math.-naturwiss. Cl., vol. 113, Abt. I, p. 1.
1909 A. Himmelbauer, Tschermaks Min. Petr. Mitt., vol. 28, p. 153.
1910 F. Rinne, Neues Jahrb. Min., vol. 1, p. 115.
1922 T. V. Barker, Graphical and tabular methods in crystallography. London. [M.A. **2**–1.]
1923 N. T. Belaiew, Journ. Inst. Metals, vol. 29, p. 379; Crystallization of metals. London, p. 72. [M.A. **2**–87.]
1926 J. Young, Proc. Roy. Soc. London, Ser. A, vol. 112, p. 630. [M.A. **3**–259.]
1927 O. B. Boggild, Meddel. om Grønland, vol. 74, p. 11. [M.A. **3**–535.]
1928 J. Leonhardt, Neues Jahrb. Min., vol. 58, p. 179. [M.A. **3**–533, **4**–122.]
—— S. W. J. Smith, A. A. Dee, and J. Young, Proc. Roy. Soc. London, Ser. A, vol. 121, pp. 477, 486, 501. [M.A. **4**–121.]
1930 G. Kurdjumow and G. Sachs, Zeits. Physik, vol. 64, p. 325.
—— L. J. Spencer, Min. Mag., vol. 22, p. 271.
—— J. Young, Min. Mag., vol. 22, p. 382.
1931 R. F. Mehl and C. S. Barrett, Trans. Amer. Inst. Min. Met. Eng., vol. 93, p. 78. [M.A. **5**–152.]
1932 F. Heide, E. Herschkowitsch, and E. Preuss, Chemie der Erde, vol. 7, p. 483. [M.A. **5**–300.]
1933 D. W. Smith, Trans. Amer. Inst. Min. Met. Eng., vol. 104, p. 48.
1934 W. Borchert and J. Ehlers, Zeits. Krist., vol. 89, p. 553. [M.A. **6**–11.]
—— R. F. Mehl and D. W. Smith, Trans. Amer. Inst. Min. Met. Eng., vol. 113, p. 203.
—— R. F. Mehl, C. S. Barrett, and H. S. Jerabek, Trans. Amer. Inst. Min. Met. Eng., vol. 113, p. 211.
—— Z. Nishiyama, Sci. Rep. Imp. Univ. Tôhoku, vol. 23, p. 637.
1937 C. S. Barrett, Metals Technology (Amer. Inst. Min. Met. Eng.), vol. 4, no. 5, techn. publ. no. 819.

1937 G. Derge and A. R. Kommel, Amer. Journ. Sci., ser. 5, vol. 34, p. 203. [M.A. **7**–63.]
—— R. F. Mehl and G. Derge, Metals Technology (Amer. Inst. Min. Met. Eng.), vol. 4, no. 3, techn. publ. no 797. [M.A. **7**–372.]
1938 J. D. Buddhue, Pop. Astron., Northfield, Minnesota, vol. 46, p. 282. [M.A. **7**–172.]
1939 S. W. J. Smith and J. Young, Nature, London, vol. 143, p. 384. [M.A. **7**–269.]
—— J. Young, Phil. Trans. Roy. Soc. London, Ser. A, vol. 238, p. 393. [M.A. **7**–536.]
1941 L. J. Spencer, Min. Mag., vol. 26, p. 19, pls. I, II.

The orientation of Widmanstetter figures in a random section.

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[Read November 6, 1941.]

THE problem of determining the orientation of Widmanstetter figures has recently arisen in a paper by Dr. L. J. Spencer on the Gibeon shower of meteoritic irons in South-West Africa:[1] the method of attacking it to be described here will be applied to the crystals illustrated in plate II of his paper.

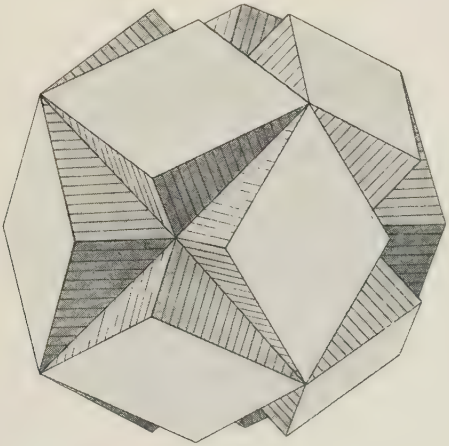

Fig. 1.

Fig. 1. Cluster of six rhombic prisms obtained by extending the faces of the regular octahedron. The basal planes (unshaded) are the faces of the rhombic-dodecahedron.

By producing the faces of a regular octahedron in all possible directions a set of six congruent prisms is formed, as shown in fig. 1. The Widmanstetter figures are the traces of these prisms in a plane of section. The section across any one of the prisms by a plane normal to its axis is a rhomb whose angles are those of a face of the rhombic-dodecahedron, that is to say, 70° 31′ and 109° 28′. If we imagine each of the prisms

[1] L. J. Spencer, Min. Mag., 1941, vol. 26, p. 19, pls. I, II.

to be a right prism closed at one end by such a face, and at the other end by the plane of section, then the problem resolves itself into finding the angle between the terminal plane $d(110)$ of a prism and the section plane; and the angle between one of its lateral faces $o(111)$ and the section plane, given their traces on this latter plane.

To do this, the Widmanstetter figures are traced in ink on tracing-paper, and from this transferred in pencil on to a plate of ground glass. Next, a rhomb having the shape of a rhombic-dodecahedral face is cut out of cardboard and set up normal to a parallel beam of light, conveniently done on an optical bench: the glass is then held so as to receive the shadow of the rhomb. By tilting and turning the glass, the edges of the shadow can be brought into approximate coincidence with two of the traces. When this is so, the plate is lowered parallel to itself until its bottom edge becomes embedded in a lump of plasticine: the glass is now self-supporting, and final adjustments are easily made. The edges of the shadow are measured with a pair of dividers. The size of the cardboard rhomb which can be used will depend on the aperture of the collimating lens employed. The edges of the one I used measured 2 cm., and the drawings which have subsequently to be made were done on a scale of one inch to a centimetre.

Suppose only two concurrent straight lines are drawn on the glass, then it may be set in an infinite number of positions, and an infinite number of shadow-parallelograms can be formed having the same angle. If now a third line be introduced forming a diagonal, then for a given cardboard rhomb the size and shape of the shadow become uniquely determined and it remains only to measure the edges of the shadow. Having got the unique parallelogram, it will be found to fit the prism in two equivalent positions (compare s_1 and s_2 of fig. 3).

On applying the method to the crystal occupying the left-hand half of plate II of Dr. Spencer's paper, the edges of the shadow were found, as a mean of three determinations, to be 2·00 and 2·64 cm. In fig. 2, draw *abcd* to represent the cardboard rhomb with sides 2 inches in length. Produce *ab* to serve as the ground line: draw lines perpendicular to this from the vertices *c* and *d*. Since the length of the shadow of *ab* is the same as *ab* itself, viz. 2 cm., its vertical and horizontal projections coincide. To find the vertical projection of *bc*, mark off *be* on the ground line equal to *bc*: through *e* draw a perpendicular to *be* and on it locate the point *e′*, where *be′* equals the true length of the shadow of *bc*, viz. 2·64 inches: through *e′* draw *e′c′* parallel to the ground line, intersecting the perpendicular from *c* in *c′*. Complete the parallelogram

hbc'd'. We have now got the horizontal and vertical projections of the section plane: from these the angle which it makes with the horizontal plane *d*(011) and with an adjacent face *o*(111) can be found by the usual methods of descriptive geometry. Thus, denoting the section plane by *s*; to find the angle *s*:(011). Since the plane containing the dihedral angle is perpendicular to both faces, through *b* draw *bh* per-

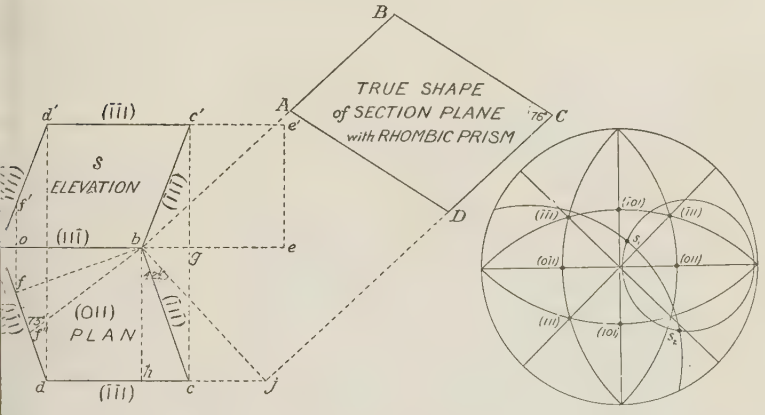

Fig. 2. Fig. 3.

Figs. 2 and 3. Geometric and stereographic projections of the section plane in the first crystal.

pendicular to *dc* and intersecting it in *h*. From *h* lay off *hj* along *dc* produced, equal to *cg*. Then *hbj* is the angle required. Similarly, to find *s*:(111); from *b* draw *bf* perpendicular to *ad*, meeting it in *f*. From *f* draw a line of correspondence intersecting the ground line in *o* and *l'* in *f'*. Along *fd* mark off *ff''* equal to *of'*. Then *ff''b* is the angle required. The true shape of the section plane can be got by erecting perpendiculars to *bj* through its extremities; from any point *A* on one of them mark off *AB* 2 inches in length and draw *AD* equal to 2·64 inches. The completed parallelogram *ABCD* corresponds to that in the top right-hand corner of Dr. Spencer's fig. 5.

Having found the dihedral angles *s*:*d*(011) = 42½°; *s*:*o*(111) = 73°, draw a stereographic representation of the octahedron-dodecahedron combination projected on a plane parallel to (001), as in fig. 3. About a dodecahedral pole, say (011), draw a small circle of radius 42½°; and about an octahedral pole at right angles to (011), say (1$\bar{1}$1), draw a small circle of radius 73°: these small circles intersect in the points s_1 and s_2 either of which may be the pole of the section plane. From

this projection I find graphically $s_1{:}d(101) = 64°$; $s_1{:}c(010) = 83\frac{1}{2}°$. From Dr. Spencer's projection (fig. 6 of his paper) I find the comparable values $s : d(0\bar{1}1) = 63\frac{1}{2}°$; $s{:}c(001) = 84\frac{1}{2}°$.

Two matters call for special comment, first the choice of traces in the optical part of the work; and secondly the choice of poles in the stereographic projection. It is sometimes possible to bring the shadow into coincidence with two traces which ought not thus to be associated. If the choice has been rightly made, then the data obtained enable us to determine (by drawing) the traces yielded by another prism, say one at right angles to the first, and these also will agree with actual traces in the photograph. In this connexion the model shown in fig. 1 is very helpful; by turning it about and comparing its various aspects with the photograph a proper choice of traces can soon be made. In the case of the left-hand crystal this difficulty scarcely arises. The model is also of great use in the choice of poles in the stereographic projection; by considering the direction in which the long diagonal of the rhomb runs, the range of choice is reduced from that between six poles to that between four.

The crystal on the right-hand side of plate II will now be considered. Ten measurements were made of shadow edges brought to coincidence with a pair of traces, and using the mean of these the following angles were found: $s{:}d(011) = 31\frac{1}{2}°$; $s{:}o(111) = 78°$. These two angles form the basis on which the synthesis of the Widmanstetter figures was effected, the results being shown in fig. 5. A stereographic projection was first made similar to fig. 3, in the manner already described, the basal faces being assigned the symbols (011) and ($1\bar{1}1$) respectively. The projection was then redrawn on the plane of section, as in fig. 4. From this other interfacial angles were taken as required and the parallelogram of traces due to any particular dodecahedral face determined by the descriptive methods. The parallelograms thus derived are shown in fig. 5, the symbol of the zone plane to which each is due being indicated. It will be seen that all the octahedral traces dealt with by Dr. Spencer are accounted for. Turning to the model shown in fig. 1, it is easily seen that the diagonals of the cardboard rhomb may correspond to an edge of the form $c(100)$. Thus the diagonal marked in the parallelogram [101] may be the trace of $c(\bar{1}00)$, agreeing exactly with the vertical line in Dr. Spencer's plate which he also assigns to that form. No other diagonals have their counterpart in the photograph, and two conspicuous traces remain unaccounted for: these are the short band forming a hook at the top of the vertical band ($\bar{1}00$), and a series

f parallel striations at right angles to it near the boundary of the two rystals.

At this stage some difficulty was experienced in finding faces to which hese lines might possibly be assigned. The traces of the icositetra-edron (211) were determined, but they failed to meet the requirements

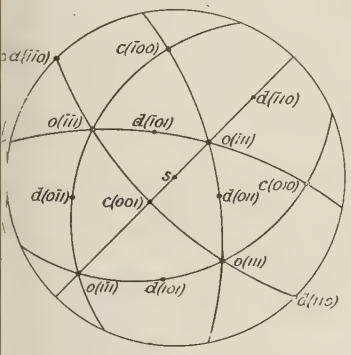

Fig. 4.

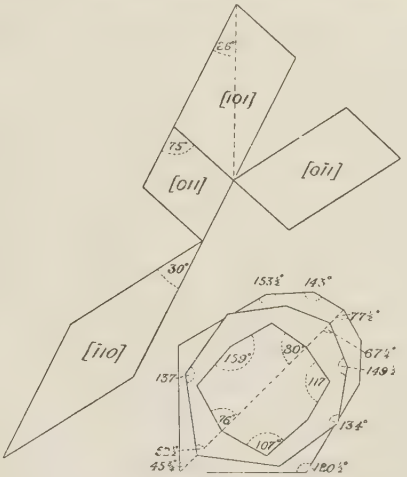

Fig. 5.

Figs. 4 and 5. Stereographic and geometric projections of the section plane in the second crystal.

f the case. The traces of the hexakisoctahedron (321) were also in-estigated, the form being conveniently dealt with by resolving it into hree pyramids (*hk*1), (*hk*2), and (*hk*3), and finding the traces of each ne separately: the polygons in the right-hand bottom corner of fig. 5 epresent them. On drawing these to a convenient scale on tracing-aper and moving them about over plate II they will be found to ccount for the lines mentioned at the end of the last paragraph. They lso account for those short bands in the centre and half-way down the ight-hand margin of the plate, which make a very acute angle with he octahedral traces; and for the striations running horizontally at the op of the plate. Thus the hexakisoctahedron (321) affords a complete e metrical solution. But Dr. Spencer informs me that (321) is not kely to occur: this being so, the mineralogical solution is yet to seek.

In conclusion, I wish to express my thanks to Dr. Spencer for much alued encouragement.

On the origin of the name 'quartz'.

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[Read November 6, 1941.]

QUARTZ is the commonest of minerals and reference to any dictionary will show that it is crystalline silica, but how or when this substance acquired the name quartz seems to be a still unsolved mystery.

Theophrastus, the pupil and successor of Aristotle, in his book on stones (19), mentions among other stones used for engraving seals, a stone called crystal (*κρύσταλλος*). This name, apparently, is derived from *κρύος*—icy cold, and *στέλλειν*—to contract. It would seem from this that the ancient Greeks, as implied by Pliny, believed crystal (modern quartz) to be a variety of supercooled ice. In point of fact the formation of crystal in nature is explained by the earliest writers in a different way. Diodorus Siculus (*circa* 30 B.C.) suggests that crystal was formed from water hardened by heavenly fire, while Pliny the Elder (*circa* A.D. 60) says that crystal is 'a substance which assumes a concrete form from excessive congelation', and goes on to explain that crystal is only to be found 'in places where the winter snow freezes with the greatest intensity' (15, Book 37, 2, 9). Pliny's description of crystal, however, leaves no doubt that he applied this name to the crystalline variety of silica which is now called quartz.

This meaning of the word crystal survived until almost the end of the XVIIIth century and was then replaced by the name quartz. How and why did this change occur, and what is the origin of the name quartz?

Apparently the first direct reference to a substance called 'quertz' is to be found in a little booklet entitled 'Eyn Nützlich Bergbüchlein' published anonymously in Augsburg probably in 1505 and subsequently republished in 1518, 1527, 1534, and 1539. Hoover (3) and Adams (1) ascribe the work to a learned Freiberg physician Ulrich Rühlein von Kalbe (Calbus), and claim that it is the earliest printed manual on ore-deposits. Its author, among other things, gives a number of names and technical terms used by the Saxon miners. 'In describing silver veins, of peculiar interest is the mention of the association of bismuth (*wis-*

muth), this being, we believe, the first mention of that metal, galena (*glantz*), quartz (*quertz*), spar (*spar*), hornstone (*hornstein*), ironstone and pyrites (*kies*), are mentioned as gangue materials. . . . So far as we know, this is the first use of any of the terms in print' (3, p. 612).

Another Saxon physician interested in mining matters, Georg Bauer, better known as Agricola, mentions the name quartz in his first book on mineralogy and mining entitled 'Bermannus sive de re metallica' published in Basel in 1530. In this book, which I have consulted in Italian translation (2), there are two passages in which the name quartz (*quarzo* in Italian) is mentioned. Here is the first passage in English translation (pp. 449 verso, 450 recto): 'The sparks of the same gold are seen to be almost attached to a species of a certain very white stone called by us [Saxon miners] quartz, and which is excavated in Cottenheide, and as far as I know your Nevio has seen it.' The second passage reads thus (p. 466, verso): 'This is another kind of stone, which at times is transparent, and is called by us quartz; sometimes it is very white, sometimes yellowish and sometimes bluish.' The third reference to quartz in Agricola's works is in his 'Interpretatio Germanica vocum rei metallicae' (1546) where, in classifying stones according to their fusibility, Agricola places in his third and most refractory class 'quertze oder kiselstein'.

These, as far as I know, are the only references to quartz in Agricola's works. Elsewhere he speaks of crystallum, silicum, silex, silice, &c. In Hoover's translation of Agricola's 'De re metallica' these names are translated as quartz or silica.

Neither Kalbe nor Agricola provides us with a precise description of the stone called quartz (quertze or quertz) by the Saxon miners, but we can assume that it is a vein-stone, usually white in colour and very refractory. There is no suggestion whatever that quartz is identical with crystallum, which is described separately, and it is probably safe to assume that originally quartz referred only to the compact vein-quartz. The name quartz is a puzzle to German etymologists and no derivation of it has been as yet proposed. Here is my tentative attempt to explain its origin.

The Saxon miners called large veins—Gänge, and the small cross veins or stringers—Querklüfte. The name ore (Erz, Ertz) was applied to the metallic minerals, to the gangue or to the vein material as a whole. In the Erzgebirge, silver ore is frequently found in small cross veins composed of silica. It may be that this ore was called by the Saxon miners 'Querkluftertz' or the cross-vein-ore. Such a clumsy word as

'Querkluftertz' could easily be condensed to 'Querertz' and then to 'Quertz', and eventually become 'Quarz' in German, 'quarzum' in Latin, and 'quartz' in English.

An additional support for this hypothesis comes from Cornwall where the old name for crystalline silica was 'cross-course spar'. This name is mentioned by Garby (10) in 1848 in the following passage: 'Radiated Quartz is exclusively found in cross-courses, and is thence called by the miners cross-course spar.' I am informed, however, by Mr. Arthur Russell, that this name is very old, and that it was mentioned by some authors prior to Garby. The term 'course' in Cornish mining dialect means a lode or a vein. It is quité plausible that the term 'cross-course spar' is an adaptation of the German term 'Querkluftertz', as the revival of mining in England during the Renaissance period was greatly influenced by the Saxon miners. The name spar was persistently applied to crystalline silica in Cornwall. Thus Borlase (6) writes: 'I must rekon what the surface of the land in most parts of Cornwall, yields in great plenty, I mean an opaque whitish debased crystal, commonly (but indeed erroneously) called white spar. . . . This stone by the Germans is called Quartz, and because we want a name for it in English, it will be so called for the future.' A similar opinion is expressed by Pryce (17): 'What is vulgarly called Spar with us, and which is so plentifully scattered upon the surface of every heathy common, is not the real Spar; and is, by most Lithologists better known by the German name of Quartz, for want of a proper English appelative.'

Leaving the verification of my guess to expert philologists, I shall now follow the subsequent history of the name quartz.

Writers on minerals and stones of the XVIth and the XVIIth centuries—such as Gesner, Cesalpino, Boetius de Boot, Caesius, Aldrovandus, and Lovell –never mention the name quartz. Apparently this name had not then left the confines of its native Saxony. But that it was used in Saxony is testified by an English traveller E. Brown, who in a book (7) published in 1685 states that in the Freiberg mines 'much of their ore is washed, especially the poorest, and that which is mixed with stones, quarts, or sparrs'; and also by Henckel, the director of Freiberg mines, who in 1725 published his famous book 'Pyritologia' (12). Discussing pyrite, Henckel, for example, writes that it is found 'in Marbles, called in the language of Miners, *horn-stone*, and resembling *quartz*' (English translation, p. 44). He also mentions that silver is found in quartz (p. 44) and that the rock-crystal (Bergcrystal) is sometimes indistinguishable from quartz (p. 74). It is clear, however, that

Henckel considers quartz and rock-crystal to be distinct species of stones.

As already mentioned the name 'quartz' has appeared in an English book in 1685. This name is again mentioned by Woodward in his catalogue. Apparently a certain Herr von Schonberg, either a mineral collector or a mining engineer, sent some mineral specimens to the famous Doctor John Woodward and one of them bore the following label: 'Cristalli candidae, Eibenstock in Saxonia. Dursichtige Weise Quartz Strahlen; i.e. transparent, white, radiated Quartz.' This is how it is recorded in Woodward's catalogue published in 1728 (22, p. 13). That the name quartz was strange to Woodward is shown by the fact that it is not mentioned in his comprehensive account of minerals and rocks (23).

Apparently the name quartz also reached Sweden in the first half of the XVIIIth century. Wallerius in his Mineralogy (21) mentions quartzum (with reference to Linnaeus) and places it in the Genus XIII, together with agate, silex, flint, onyx, &c., and again in Genus XV (probably vein-quartz). The crystalline variety of silica (Crystallus exagona non colorata, Crystallus montana) is described by Wallerius as a distinct species in Genus XVI. This shows that the name quartz was still applied to a compact variety of silica and not to rock-crystal.

A great advance in mineralogy was made by the application of chemical analysis. The first to introduce the qualitative methods of chemical analysis in a systematic way in mineralogy was the professor of chemistry in Berlin, J. H. Pott. In his 'Lithogeognosy' (16) he described chemical tests on various minerals and his conclusions were that quartz, crystal, flint, sand, &c., were of similar composition (French translation, p. 169). He also made a very important discovery that quartz and after fusion with alkali yielded 'liquoris silicum' which coagulated into a jelly on addition of an acid. In spite of this observation quartz and crystal were still described as separate species. It is also clear from the following quotation that Pott confused quartz and felspar: 'J'appelle Quartz cette espece de Pierre blanche qui se trouve aboudamment avec les Mines, & qui fait feu étant frappée contre l'Acier. Il y en a de transparent, crystallin & pur, qui n'entre pas en fusion avec les Terres Alcalines. Mais la plus grande partie des Quartz est plutôt opaque & d'une couleur de lait; & pour la distinguer de l'autre, je l'appellerai *Quartz Spathique*, ce dernier entre parfaitement en fusion avec les Terres Alcalines' (p. 32). It is a remarkable fact that such a

common mineral as felspar began to be distinguished from other minerals only in the XVIIIth century. As shown by Zenzén (24) the name Feldtspat (i.e. field-spar) was invented in 1740 by Daniel Tilas, a Swedish mineralogist (20). It is obvious that felspar and quartz were confused by Pott and, as we shall presently see, also by Mendes da Costa. In 1757 Emanuel Mendes da Costa, a British-born Jew of Portuguese descent, published what I think is the best manual on rocks of that period. It is called 'A natural history of fossils' (14) and only the first part of the first volume was ever published. The part published contains a description of all the rocks known to science at that time. In describing granite Mendes da Costa writes, that it is composed of quartz and mica, but it is obvious that he uses the name quartz as did Pott to embrace felspar. This is clear from the following quotation: 'the basis [of granite] is of a milk white opake glossy *quartz*, of a tabulated structure, called Feld-Spath by the German writers, intermixed with lumps of a fine transparent and cristalline quartz . . .' (pp. 273–274). The same dual meaning of the name quartz is found in Mendes da Costa's notes appended to the translation of Cronstedt's Mineralogy (9). On pp. 57–58 of this book the name quartz is used synonymously with 'cristallus montanus' and the foot-note by Mendes da Costa is as follows: 'I shall adopt this name of quartz in English as it has already gained access into the other European languages' (p. 57). But on page 72 Rhombic Quartz, Spatum scintillans, or Feltspatum is mentioned and the corresponding foot-note is as follows: 'The Germans and other nations call this substance Feld-spat, that is feild or vague spar; a name very inadequate to its nature, as it touches no wise on the sparry class. I have therefore, in my Lectures, given it the English name of Rhombic Quartz, a name very significant, as the name quartz expresses its class; and the quality of it, of always breaking into angular (rhombic) fragments, is also expressed by the adjective of rhombic.' This confusion between quartz and felspar did not last long and the application of the quantitative chemical analysis to minerals by Bergman (5) finally separated the two minerals. From then on, quartz became synonymous with rock-crystal.

The reason for this replacement of one name by another, viz. crystal by quartz, is obvious. It is because in the XVIIth century the name crystal acquired a wider meaning and its retention as the name of a particular mineral would lead to ambiguity. This necessity of change is reflected by Mendes da Costa in the following words: 'The author uses the term Quartz cristals for the true cristals; for all foreign

authors call figured spars also cristals; and distinguish them by the name of spath or spar cristals' (9, p. 5, footnote).

The study of crystals began with Nicolaus Steno, a Dane residing in Italy, who in 1669 published his famous book (18). In this work he was very careful to distinguish between quartz, which he called cristallus or cristallus montium, from other types of crystalline minerals, which he called 'angulata corpora' (singular—corpus angulatum). But that the name crystal was applied to other 'corpora angulata' besides quartz is shown by the title and the substance of a work of another learned Dane, Erasmus Bartholinus (4), published in the same year 1669. The works that followed, such as those of Guglielmini (11), Hottinger (13), and Cappeller (8), show the confusion caused by the use of the name crystal in two senses, and the re-emergence of the old Saxon mining term—quartz, was probably a welcome solution of this dilemma. In any case in the second half of the XVIIIth century quartz became established as a name of a particular mineral and the name crystal became a generic term synonymous with the old term 'corpus angulatum'.

It is a pleasure to record my indebtedness to Mr. C. E. N. Bromehead and Mr. Arthur Russell for their kindness in providing me with additional references.

References.

1. Adams (F. D.). The birth and development of the geological sciences. London, 1938. [M.A. 7–312.]
2. Agricola (G.). De la generatione, &c. Venice, 1550.
3. —— De re metallica. Translated from the first Latin edition of 1556 by H. C. Hoover and L. H. Hoover. London, 1912.
4. Bartholinus (E.). Experimenta cristalli Islandici disdiaclastici. Copenhagen, 1669.
5. Bergman (T.). Manuel du minéralogiste; ou sciagraphie du règne minéral, distribué d'après l'analyse chimique. French translation, Paris, 1784.
6. Borlase (W.). The natural history of Cornwall. Oxford, 1758, p. 91.
7. Brown (E.). Travels in divers parts of Europe . . . with some observations on the gold, silver, copper, quick silver mines. . . . London, 1685, 2nd edition, p. 170.
8. Cappeller (M. A.). Prodromus crystallographiae de crystallis improprie sic dictis commentarium. Lucerne, 1723.
9. Cronstedt (A. F.). An essay towards a system of mineralogy. Translated by G. von Engestrom. Revised and corrected by E. Mendes da Costa. London, 1770.
10. Garby (J.). A catalogue of minerals found in Cornwall, with their localities. Trans. Roy. Geol. Soc. Cornwall, 1848, vol. 7, p. 74.
11. Guglielmini (D.). Riflessioni filosofiche dedotte dalle figure de' sali. Bologna, 1688.
12. Henckel (J. F.). Pyritologia oder Kiess-Historie. Leipzig, 1725. English translation: Pyritologia; or, a history of the pyrites, &c. London, 1757.

13. Hottinger (J. H.). Dissertatio de crystallis. Zürich, 1698.
14. Mendes da Costa (E.). A natural history of fossils. London, 1757, vol. 1, part 1.
15. Plinius Secundus (C.). Naturalis historia. The natural history of Pliny. Translated by J. Bostock and H. T. Riley, London, 1855–57.
16. Pott (J. H.). Lithogéognosie, ou examen chymique des pierres et des terres, &c. Paris, 1753.
17. Pryce (W.). Mineralogia Cornubiensis. London, 1778, p. 27.
18. Steno (N.). De solido intra solidum naturaliter contento dissertationis prodromus. Florence, 1669.
19. Theophrastus. History of stones. Edited and translated by Sir John Hill. London, 2nd edition, 1774.
20. Tilas (D.). Tanckar om malmletande i anledning af löse gråstenar. Vet. Akad. Handl. Stockholm, 1739–40, vol. 1, pp. 198–201.
21. Wallerius (J. G.). Mineralogia, eller mineralriket. Stockholm, 1747.
22. Woodward (J.). Additional English native fossils in the collection of J. Woodward. London, 1728, vol. 2, [Supplement] part 1. A catalogue of the foreign fossils, &c.
23. —— Fossils of all kinds digested into a method, &c. London, 1728.
24. Zenzén (Nils). On the first use of the term "feldtspat" (= feldspar etc.) by Daniel Tilas in 1740. Geol. För. Förh. Stockholm, 1926, vol. 47 (for 1925), pp. 390–405. [M.A. 3–468.]

Lamellar structure in orthopyroxenes.

(With Plate IV.)

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[Read November 6, 1941.]

THE fine lamellar structure (pl. IV, fig. 1 *a* and *b*) which is described here is very common in the orthopyroxenes of plutonic and regionally metamorphosed rocks. This structure can be seen under crossed nicols in sections inclined at a high angle to the optic axial plane (100), except on those sections which make a low angle with (001). When the main part of the crystal is in extinction, the fine lamellae stand out because their extinction position is different from that of the main crystal. Although this structure is common, it is not described in any of the widely used text-books, but several descriptions and references to it have been published in recent years. The purpose of this paper is to draw attention to the nature of this lamellar structure.

Previous References.

In several text-books rather vague remarks are made about secondary lamellar twinning due to deformation. These remarks refer to the work of Bücking (1883) and Mügge (1898) and they have been repeated on numerous occasions with neither drawing nor fuller description. Bücking described lamellar twinning on a flat dome face (104)[1] in a bronzite from Ultenthal which he said showed characteristics of glide-twinning. Mügge discusses the bending of the (100) cleavage about the *b*-axis which he ascribes to translation on the (100) plane along the *c*-axis, and he suggests that the lamellar twinning of Bücking is due to the same cause. The structures described by Bücking and Mügge are found also in monoclinic pyroxenes and are clearly different from the fine lamellar structure with no bending which we are discussing here. In the text-book of Rosenbusch-Wülfing (1927) mention is made of a structure, described as lamellar intergrowth, according to a definite law, of monoclinic and orthorhombic pyroxenes. This microperthitic structure is common in

[1] The orientation $a > b$ is used throughout this paper.

pyroxenes of some plutonic rocks, but is quite different from the structure under discussion here.

In describing an intergrowth of clino- and orthopyroxenes Wager and Deer (1939) say that 'It does not resemble the fine-scale structure, parallel to the optic plane which has frequently been observed but not yet explained'. Chudoba (1932) mentions in his text-book the occasional occurrence of a polysynthetic twin structure which may be partly due to translation on (100). As he does not say anything about bending, he may be referring to the fine-scale lamellar structure.

In recent years several specific occurrences of this structure have been described and different explanations offered. Wagner (1924, p. 41) in describing a bronzite from the Bushveld complex says: 'The bronzite often exhibits fine polysynthetic twinning parallel to the plane (100). The twin lamellae, which are very thin, have an extinction $c : Z$ of about 9°. The twin[n]ed portions are sometimes irregularly distributed through the untwinned, and a core of twinned bronzite was found in one instance to be surrounded by an irregular shell showing no trace of twinning. The prevalence of this twinning, which is exhibited by the bronzite of the bronzitites and allied rocks throughout the Bushveld complex, appears to support Zambonini's view that all enstatite (or bronzite) is clino-enstatite in which the twinning is sub-microscopic.'

Phemister (1928) describes with a photomicrograph the same lamellar structure in orthopyroxene in the Cobalt diabase. The lamellae occur sometimes in patches, the junction-plane is the optic axial plane, the interference-figure is of an acute bisectrix due to the main orientation of the more numerous lamellae, while the difference in extinction position between the two groups of lamellae is 15°. The explanation offered is that the obliquely extinguishing lamellae are of a highly magnesian monoclinic pyroxene which has its optic axial plane perpendicular to that of the hypersthene and so low a birefringence that it does not affect the interference-figure given by the hypersthene.

In describing an iron-rich hypersthene from a eulysite, Sundius (1932) remarks on the lamellar structure which appears only in sections perpendicular to the optic axial plane and within the acute optic axial angle. As the junction-plane of the lamellae is (100) he says the structure cannot be due to twinning, and he ascribes it to intergrowth of the orthorhombic mineral with a monoclinic lime-bearing pyroxene, showing oblique extinctions of 4–12°, but these lamellae form only 5 % of the whole mineral.

Guimarães (1930), in describing quartz-gabbros from north Brazil,

gives photographs of lamellar hypersthenes which appear to be similar to those studied in this paper. The structure is explained as being due to intercalations of magnesian diopside.

Bowen and Schairer (1935) also mention lamellar structure which they noticed in the South African bronzite used for inversion experiments, and they state that 'These minerals usually show a rather obscure lamellar twinning with extinctions up to about 9° against the composition plane'. They point out that this is quite different from the twinning of the true clinopyroxenes and also that this 'twinning' does not appear to be on the flat dome (104).

Scholtz (1937) studied the lamellar structure in orthopyroxene from hyperites and picrites and he gives a photomicrograph of the structure. He states that the lamellation, which is not related to the composition of the mineral, is developed parallel to (100), the lamellae having the a direction in common while the β and γ directions of different sets are inclined to each other usually at angles of 5–11°. Sections in the zone [100] sometimes show irregular patches which extinguish uniformly along with one set of lamellae. Scholtz suggests the existence of some twinned relationship, although he admits that the evidence is by no means conclusive, and he refers to the hypothesis that orthopyroxene may be composed of sub-microscopically twinned monoclinic individuals. Another description of this structure from the Bushveld complex is given by Nel (1941), who mentions that the striations sometimes pinch out before they reach the borders of the crystals and that there may be patches of crystal free from striations.

Hess and Phillips (1938) state that the lamination is entirely due to the presence of very fine lamellae of another mineral, which form thin sheets, 0·002 mm. thick, parallel to the optic axial plane and which have approximately the same mean refractive index as the host crystal, regardless of the composition. The lamellae have large extinction-angles, so it appears that they are monoclinic, probably of the diopside-hedenbergite series, with approximately the same Mg/Fe ratio as the host, and their optic axial plane is at right angles to that of the orthorhombic host crystal. These diopsidic lamellae formed as a result of exsolution on cooling from an orthopyroxene and supply the 2 % of CaO which is present in many analyses of enstatites and hypersthenes. Rapid cooling prevents the exsolution in the orthopyroxenes of volcanic rocks.

The lamellar structure has been seen in sections of the Manegaon meteorite. In a recent description of the Chicora meteorite, Preston, Henderson, and Randolph (1941) refer to the occurrence of fine lamellar

twinning in a few grains of hypersthene, and this may be the same structure.

In considering the literature it is sometimes difficult to decide whether the reference is to the same structure. The lamellar structure described here is quite different from the glide-twinning on a dome face and from the deformation shown by the bending of the (100) cleavage, both of which are mentioned in German text-books. It is also different from the common lamellar intergrowths of ortho- and clinopyroxenes described by several authors, because in these the two sets of lamellae have different birefringences. If we consider the cases where the authors appear to be dealing with the same structure as that under consideration, the explanations offered fall into two groups.

1. Polysynthetic twinning.

2. Intergrowths of the orthopyroxene with a clinopyroxene of the nature of a clinoenstatite or a magnesian diopside. The optic axial plane of the clinopyroxene is (010) and that of the orthopyroxene is (100). The contact plane of the lamellae is (100) and for sections which show the intergrowth, the birefringences of the two minerals are very similar.

Hess and Phillips suggest that, on slow cooling, exsolution of diopsidic lamellae occurs, owing to the existence of about 2 % of CaO in most orthopyroxenes. Although orthopyroxenes of lavas have similar amounts of CaO they do not show lamellae, and the non-occurrence of the intergrowth is ascribed to rapid cooling. Hess and Phillips go on to suggest that the amount of the intergrowth is dependent on the amount of CaO present. The only definite statement about the presence or absence of this lamellar structure in an orthopyroxene of low CaO content is that of Tilley (1936) who describes the iron-rich hypersthene from the eulysite of Loch Duich, Scotland, as having this structure well developed, although it has only 0·83 % CaO. Foshag (1940) says that in the enstatite (0·32 % CaO) of the Shallowater meteorite, 'undulatory and other extinction anomalies are common, including a hackly pattern suggestive of twinning'. This may refer to the lamellar structure. In view of the scantiness of the data, the suggestion of Hess and Phillips that lime-poor orthopyroxenes can in many cases be recognized by the fewness of their lamellae appears to be unsupported. It seems that orthopyroxenes of any composition can have atoms of (Mg,Fe) replaced by atoms of Ca, to the amount corresponding to 2 or 3 % CaO, without destroying the symmetry of the crystal. Reference to CaO or diopsidic molecules being soluble in crystals of orthopyroxene does not help in the understanding of problems of this kind.

X-Ray Study.

Several specimens from different localities were used. After examination on the universal stage, suitable sections were cut out and studied by means of X-rays, the optical information being used in the pre-

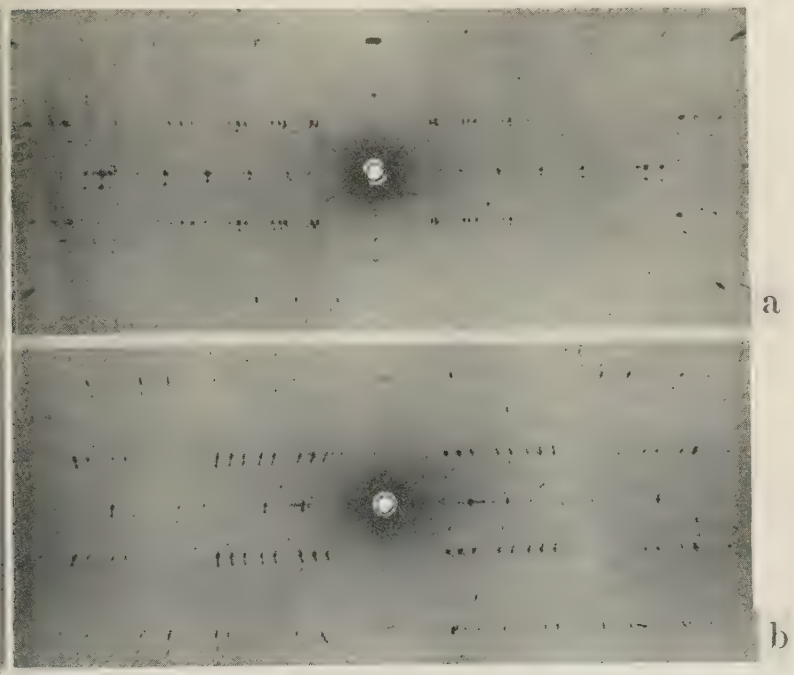


Fig. 2.

Fig. 2. X-ray photographs of orthopyroxenes with lamellar structure. Co-Kx radiation; cylindrical camera of radius 3 cm. Approx. $\frac{3}{5}$ original size.

(*a*) Hypersthene from norite: Baste, Harz. Oscillation-axis *c*; oscillation-angle $7\frac{1}{2}°$ on either side of *a*-axis.

(*b*) Hypersthene from quartz-biotite-norite: Glen Buchat, Aberdeenshire. Oscillation-axis *c*; oscillation-angle $7\frac{1}{2}°$ on either side of *b*-axis.

liminary setting. The oscillation photographs taken about the *b*-axis are quite normal, although in two cases a slight elongation of the spots can be seen. In the photographs taken about the *c*-axis, however, (fig. 2*a* and *b*) there are additional spots forming a complete oscillation photograph of a similar crystal with its *c*-axis inclined at about 7° to that of the main crystal in the (010) plane. The spots of this tilted oscillation photograph match those on the layer-lines of the main photo-

graph and are connected to them by Debye-Scherrer curves on which are superposed, in some cases, the spots from other preferred orientations. These photographs show that most of the subsidiary lamellae, which produce the tilted oscillation photographs, are inclined to one side of the main crystal and that one or two orientations are strongly preferred. But the elongation visible in the strong spots shows that a small proportion of the material is inclined on both sides of the main crystal at angles up to about 15° from it. From this evidence it is clear that:

(*a*) The lamellae are orthopyroxenes of the same composition as the main crystal.

(*b*) The lamellae are inclined to the main crystal in the (010) plane of the latter. (In some cases a slight inclination of the *b*-axes of the two sets of lamellae can be detected, so that the displacement is not always strictly in the (010) plane.)

(*c*) The structure is not a regular twin structure because there is a range of orientations.

Optical Study.

Examination on the universal stage shows that:

(*a*) The lamellae form very thin irregular sheets, 0·001–0·002 mm. thick, parallel to (100), which have a bent, pinched-out appearance (see fig. 1*b*, pl. IV).[1]

(*b*) The refractive indices and the birefringences of the sets of lamellae are equal.

(*c*) The lamellae of the subsidiary orientations can be distinguished from those of the main crystal only under crossed nicols by their different extinction positions.

When the pole of the section is (010) the lamellae are very thin and the boundary lines are sharp: but as the pole is inclined away from the *cb* plane, the lamellae become thicker and eventually become invisible when the pole makes an angle of more than about 30° with the *cb* plane. When the pole is inclined in the *cb* plane the lamellae retain their sharpness until the pole approaches (001), when they disappear. On (010) the extinction-angle of the fine lamellae varies up to about 8°, but thicker patches remain in extinction over a large angle. In the 45° position all trace of the structure has vanished and the birefringence colour is quite uniform. The thicker patches which appear to give

[1] This appearance is seen, also, in fine lamellar structures of different kinds in other minerals.

higher extinction-angles are composed of several lamellae which the eye cannot separate, and their optical behaviour is due to the superposition of several crystals. When the pole of the section is inclined to (010), the extinction-angle varies up to 90° (slow vibration-direction to trace of junction-plane).

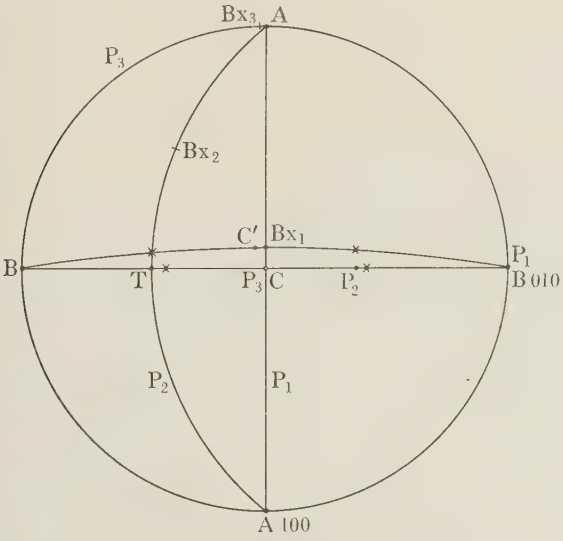


Fig. 3.

Fig. 3. Stereogram showing extinction-angles in an inclined lamella of an orthorhombic pyroxene with 2V 90°.

C and C' are the poles of the c-axes of the main crystal and an inclined lamella respectively, while × marks the poles of their optic axes. P_1, P_2, P_3 are the poles of sections and the corresponding great circles. Extinction-angles are measured from the slow vibration-direction to the trace of the (100) plane of the main crystal.

For P_1 the extinction-angle is C : $Bx_1 = 10°$,
„ P_2 „ „ T : $Bx_2 = 45°$,
„ P_3 „ „ B : $Bx_3 = 89°$.
The extinction of the main crystal is straight in each of these cases.

In fig. 3 the optic orientation of an orthopyroxene with 2V 90° is represented on a stereogram, along with that of a similar crystal displaced relative to the first nearly in the *ca* plane. If we consider the pole P_1 of a section which coincides with (010) of the main crystal, we see that the extinction-angle of the second crystal is equal to the displacement of the *c*-axes projected on to the *ca* plane (all extinction-angles are measured from the slow vibration-direction to the trace of the junction-plane, i.e. approximately the *cb* plane of the main crystal).

But if we take the pole P_2 the extinction-angle is 45°. It is well known that sections nearly perpendicular to an optic axis of a biaxial crystal can show all variations of extinction-angle. On (001) the extinction would, of course, be straight if the displacement were in the *ca* plane, but even if it is 5° off this, as in the diagram, the extinction is too small to be noticeable (see fig. 3). In this discussion we have assumed that the pole of the main crystal moved in the *cb* plane so that its extinction would always be straight, although it changes from 0° to 90° at the optic axis. But if the section were tilted out of this plane, the main crystal can show any extinction-angle. We considered it in the first way because the important thing is the difference between the extinction positions of the two crystals in any given orientation, as it is that which makes the lamellae visible.

The lamellae become invisible in two ways as we have seen: first, when the section makes too low an angle with the plane of junction so that the structure is only seen on sections which are nearly perpendicular to the *cb* plane: secondly, when the difference in extinction-angle becomes very small, as happens when the pole of the section approaches (001). The undulose extinction which is always present indicates intermediate positions of displaced crystals, but the amount of material in these positions is smaller than that in definite positions. Most of the lamellae, also, extinguish to one side of the extinction position of the main crystal. Both these observations are supported by examination of the X-ray photograph in fig. 2, which shows Debye-Scherrer lines connecting the spots from the main and from the subsidiary lamellae, while a little elongation occurs on the other side of the main spots.

The optical behaviour of this structure has been interpreted by most authors as produced by intercalated lamellae of clinopyroxene in the same structural orientation as the orthopyroxene host (i.e. $c \parallel c$ and $b \parallel b$). But in that case the extinction-angle on a (010) section should equal the $c : \gamma$ angle of the clinopyroxene, which must be at least 22° if the crystal is clinoenstatite or magnesian diopside. Mention is made of fairly high extinction-angles of lamellae by some authors, but where it is stated that care was taken to make the observations on sections orientated parallel to (010), no angle higher than 10° is reported. Apart from a few stray lamellae and the anomalously extinguishing patches mentioned previously, no higher angle has been observed on clearly defined lamellae during the observations recorded in this paper.

A lamellar structure due to deformation has been observed in halite

and sylvine in which the doubly-refracting lamellae produced by stretching have been studied optically. The process whereby bending of parts of the crystal takes place on gliding is called 'Biegegleitung', a term which was first used by Mügge. It seems reasonable to ascribe the structure under discussion to such a process of translation on (100) in the direction [001], accompanied by bending about [010]. It would be expected that the bending might not always be strictly about [010], but the evidence shows that the divergence from this direction is never considerable.

Geological Occurrence.

Orthopyroxenes occur in basic and ultrabasic plutonic and volcanic rocks of normal type; in the rocks of the charnockite series and in those of the eclogite type; in contaminated norites; in high-grade thermally metamorphosed rocks of both igneous and sedimentary origin; in high-grade regionally metamorphosed rocks of both igneous and sedimentary origin; and in stony meteorites. Owing, however, to the scarcity of precise observations, only general and tentative conclusions can at present be reached about the geological occurrence of the lamellar structure. It does occur in many basic and ultrabasic plutonic masses, but is not seen in volcanic rocks. It is rather poorly developed in the noritic members of the charnockite series, but does not seem to be present in the more acid ones. It occurs in hypersthene-eclogites. In the contaminated cordierite-norites of Aberdeenshire the structure is found, but it dies out as the amount of magmatic material decreases and the rock becomes more like a hornfels. No orthopyroxene from a thermally altered rock has yet been seen to show this structure. It does, however, occur in katazone rocks such as eulysites and pyroxene-granulites. It is seen, also, in some meteorites. As a generalization of these observations we can say that the conditions of crystallization in an ordinary plutonic basic magma allow the best development of the lamellar structure. Conditions in the katazone, whether of intrusion or of metamorphism, also produce the structure, as do the conditions of formation of some meteorites. In the case of volcanic rocks and of thermal metamorphism the conditions are not favourable for the development of the structure. The process of cataclastic deformation, also, does not allow the structure to develop, although the 'Knickung' of Mügge and Bücking is produced in such conditions. In some cases the fine lamellae of the structure are seen to be bent by subsequent shearing.

Summary.

Previous statements about the common lamellar structure in orthopyroxenes are reviewed. New X-ray evidence is produced along with the results of optical examination of specimens from several localities. It is shown that the lamellae are composed of the same orthorhombic material as the main crystal and that the visibility of the structure is due to differences in extinction position between the sets of lamellae. These sets of lamellae have their *a*- and *c*-axes displaced relative to those of the main crystal in, or nearly in, the *ca* plane at angles up to about 10–15°. This structure appears to be due to deformation and is evidently formed during crystallization.

References.

N. L. Bowen and J. F. Schairer, The system MgO – FeO – SiO_2. Amer. Journ. Sci., 1935, ser. 5, vol. 29, p. 169. [M.A. **6**–352.]

H. Bücking, Bronzit vom Ultenthal [in Tyrol]. Zeits. Kryst. Min., 1883, vol. 7, p. 502.

K. Chudoba, Mikroskopische Charakteristik der gesteinsbildenden Mineralien. Freiburg, 1932, p. 90. [M.A. **5**–101.]

W. F. Foshag, The Shallowater meteorite; a new aubrite. Amer. Min., 1940, vol. 25, p. 780. [M.A. **8**–60.]

D. Guimarães, Provincia magmatica de Roroimã, Brasil septentrional. Bol. Serv. Geol. Min. Brasil, 1930, no. 45.

H. H. Hess and A. H. Phillips, Orthopyroxenes of the Bushveld type. Amer. Min., 1938, vol. 23, p. 450. [M.A. **7**–180.]

O. Mügge, Ueber Translationen und verwandte Erscheinungen in Krystallen. Neues Jahrb. Min., 1898, vol. i, p. 114.

H. J. Nel, The basal rocks of the Bushveld igneous complex, north of Pretoria. Trans. Geol. Soc. South Africa, 1941, vol. 43 (for 1940), p. 46.

T. C. Phemister, A comparison of the Keweenawan sill-rocks of Sudbury and Cobalt, Ontario. Trans. Roy. Soc. Canada, 1928, vol. 22, sect. 4, p. 133.

F. W. Preston, E. P. Henderson, and J. R. Randolph, The Chicora (Butler County, Pa.) meteorite. Proc. U.S. Nat. Museum, 1941, vol. 90, p. 387. [M.A. **8**–193.]

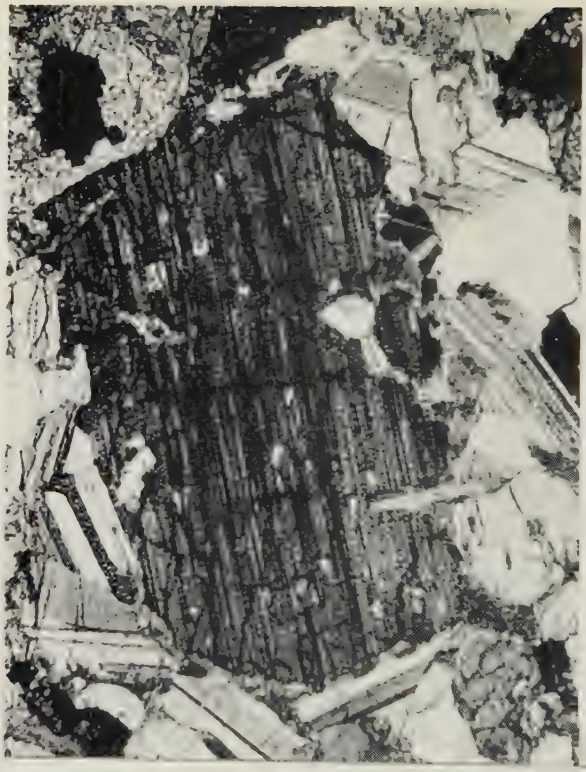
Rosenbusch-Wülfing, Mikroskopische Physiographie. Stuttgart, 1927, vol. 1, pt. 2, p. 345.

D. L. Scholtz, The magmatic nickeliferous ore deposits of East Griqualand and Pondoland. Trans. Geol. Soc. South Africa, 1937, vol. 39 (for 1936), p. 111. [M.A. **6**–440.]

N. Sundius, Über den sogenannten Eisenanthophyllit der Eulysite. Årsbok Sveriges Geol. Undersökning, 1932, vol. 26, no. 2. [M.A. **6**–118.]

C. E. Tilley, Eulysites and related rock types from Loch Duich, Ross-shire. Min. Mag., 1936, vol. 24, p. 334.

L. R. Wager and W. A. Deer, Geological Investigations in east Greenland. Part III. Meddel. om Grønland, 1939, vol. 105, no. 4, p. 83. [M.A. **8**–27.]



a

b

N. F. M. Henry: Lamellar Structure in Orthopyroxenes.

P. A. Wagner, On magmatic nickel deposits of the Bushveld complex in the Rustenburg district, Transvaal. Mem. Geol. Surv. South Africa, 1924, no. 21. [M.A. 3–44.]

Explanation of Plate IV.

Fine lamellar structure in orthopyroxenes. Crossed nicols with the main crystal in extinction position.

Fig. 1*a*. Hypersthene from olivine-diallage-norite: Whitecairns, Belhelvie, Aberdeenshire. The small light patches are orientated inclusions of clinopyroxene. ×32.

Fig. 1*b*. Hypersthene from norite: Baste, Harz. The fine lamellae are bent and pinched out. ×140.

Tricalcium disilicate (rankinite), a new mineral from Scawt Hill, Co. Antrim.

(With Plate V.)

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TRICALCIUM disilicate, first described by Shepherd, Rankin, and Wright[1] in their investigations on the lime–silica and lime–alumina–silica systems has since been reported as a constituent of technical slags.[2] An account has also been given of its occurrence as a reaction product in a glass furnace.[3]

In the ternary system CaO–Al_2O_3–SiO_2 the compound forms with pseudowollastonite–gehlenite and larnite–gehlenite two three-phase equilibrium assemblages, associations which are in part recorded in the technical products.

G. V. Wilson recorded the disilicate together with wollastonite and melilite in reconstituted limestone fragments enclosed in glass, while S. G. Gordon has described and presented an analysis of a slag composed of pseudowollastonite and the 3:2-compound approaching in composition that of the binary eutectic in the synthetic system. As minerals, the immediate associates of the disilicate in the ternary system are represented by larnite, melilite, and wollastonite at the locality of Scawt Hill, but hitherto the compound itself has not been recorded.

Recent examination of further material among the larnite-rocks of Scawt Hill has now revealed its presence in several specimens of these assemblages and it thus takes its place as a new mineral.

The identification has been facilitated by a parallel study of the compound in a number of slags. In these the relatively good form development of the crystals has permitted additional data to be obtained, and account of the mineral at Scawt Hill will therefore be prefaced by a note on the slag occurrence.

[1] E. S. Shepherd and G. A. Rankin, Journ. Indust. Eng. Chem., 1911, vol. 3, p. 211. G. A. Rankin and F. E. Wright, Amer. Journ. Sci., 1915, ser. 4, vol. 39, p. 1. [M.A. 1–320.]

[2] S. G. Gordon, Amer. Min., 1923, vol. 8, p. 110.

[3] G. V. Wilson, Trans. Soc. Glass Techn., 1918, vol. 2, pp. 181, 196.

The slags come from the old Carnforth (Lancashire) ironworks and were originally collected by Professor W. G. Fearnsides to whom I am indebted for information on their history.[1] They are well-crystallized types built up of pseudowollastonite, melilite, and $3CaO.2SiO_2$. A small amount of interstitial glass is present together with accessory calcium sulphide and some grains of metallic iron. The 3:2-compound crystallized early and forms colourless subhedral crystals partly enveloped by melilite.

Hitherto optical data on the compound have been incomplete. From synthetic melts it is described as crystallizing as rounded grains with no cleavage: probably orthorhombic, α 1·641, γ 1·650, $2V_\gamma$ large. Gordon in his description of crystals from a slag referred to them as monoclinic, optically positive, α 1·641, β 1·643, γ 1·650. He noted a perfect cleavage (100) and an extinction-angle $\alpha:c = 15°$ in the plane of symmetry. With the exception that the Carnforth slag crystals exhibit no cleavage these data are in agreement with my own observations. The habit is usually in the form of subhedral flattened or tabular grains from the broad four- to six-sided sections of which emerges γ the acute bisectrix. The optic axial plane lies in the plane of symmetry. Elongated cross-sections showing the normal emergence of the obtuse bisectrix (α) have straight extinction, β parallel to elongation, those perpendicular to β showing an extinction-angle α to the elongation taken as the trace of (001) = 15°. Besides the basal plane, prism and clinodome are frequently developed. Elongation is consistently negative. The optical properties may be summarized as follows:

Monoclinic, $b = \beta$, α : edge of (001) = 15°;
α 1·641, β 1·644, γ 1·650, $2V_\gamma$ 64°, positive.

The development of abundant $3CaO.2SiO_2$ in these slags is associated with a high lime content, indicated in the analysis that has been made of one of them. The results are set down in table I, no. 1. This slag contains approximately equal proportions of pseudowollastonite, $3CaO.2SiO_2$, and melilite. If we compare the analysis with that of the normal type of melilite slag, the chief points of difference are high lime and silica and low alumina (cf. table I, no. 4), features which account for the content of pseudowollastonite as well as that of the 3:2-compound.

The analysis may be compared with the composition of the ternary

[1] The former Carnforth ironworks manufactured pig iron from Furness haematite ore (chief gangue mineral, quartz), and Durham coke and local limestone were used in the smelting.

eutectic, pseudowollastonite–$3CaO.2SiO_2$–gehlenite in the lime-alumina–silica system (table I, no. 3).

The identification of the 3:2-compound in slags has not frequently been recorded. In a discussion on the composition of iron blast-furnace slags, McCaffery, Oesterle, and Schapiro[1] have attempted to calculate the mineral composition of slags from the analysis of the four chief component oxides, and they recognize a series of high-lime slags in which this compound is calculated to enter in large amounts. No optical examination of such slags is reported and it is doubtful whether any reliance can be placed on such calculations in view of the incompleteness of the analysis and the known variable composition of the melilite phase. Nevertheless, it seems probable that the 3:2-compound may be a not uncommon constituent of blast-furnace slags high in lime.

Table I.

	1.	2.	3.	4.
SiO_2	39·47	39·22	41·0	36·25
TiO_2	0·27	—	—	—
Al_2O_3	7·96	5·86	11·8	13·04
Fe_2O_3	nil	1·83	—	—
FeO	1·18	—	—	0·91
MnO	—	—	—	0·79
MgO	1·46	trace	—	6·37
CaO	46·39	44·56	47·2	40·60
Na_2O	0·11	—	—	—
K_2O	1·13	—	—	—
H_2O-	0·28	0·55	—	—
S	0·86	—	—	1·53 (sulphide)
Insol.	—	2·24	—	—
Total	99·11			
Less O for S	0·43			
	98·68			

1. Slag, Carnforth, Lancashire; with α-$CaSiO_3$, $3CaO.2SiO_2$, and melilite. (Analysis, Geochemical Laboratories.)

2. Limestone xenolith in glass, Kinghorn bottle works, Fife; with wollastonite, $3CaO.2SiO_2$, and melilite. (G. V. Wilson, loc. cit., p. 196.)

3. Ternary eutectic; α-$CaSiO_3$, $3CaO.2SiO_2$, and gehlenite. (G. A. Rankin and F. E. Wright, loc. cit., p. 78.)

4. Mean composition of blast-furnace slags. (National Slag Association, Symposium, Cleveland, Ohio, 1928, no. 11.)

At Scawt Hill the disilicate is found in association with the minerals wollastonite, larnite, and melilite (*a*) in melilite-rocks, (*b*) at the contact of flint nodules in the metasomatized chalk.

The melilite-rocks have arisen as the result of intense but localized soaking of solutions from the dolerite into the chalk (Min. Mag., 1931,

[1] Amer. Inst. Min. Met. Eng. Technical Pub., 1927, no. 19.

vol. 22, p. 457) and occur as small patches in the larnite-spurrite-rocks. Normally they consist of coarse aggregates of melilite and wollastonite together with iron-ores and have often undergone late-stage alteration with the development of afwillite, ettringite, and other hydrated alteration products in vugs and venules.

It is in the primary association that the disilicate is met with in several specimens as colourless rounded or irregular grains devoid of cleavage. Its common associate is melilite, but it occurs in immediate proximity either with larnite or with wollastonite.

Though insufficient material is available for quantitative analysis, microchemical tests on sections isolated from slides provide confirmatory evidence of its composition. It gelatinizes readily in weak HCl–H_2SO_4 solutions, precipitating abundant gypsum. It contains no magnesium nor aluminium and is unaffected by prolonged heating at 1100° C. Like the accompanying melilite, it has suffered the effects of late solutions and shows an interesting development of afwillite ($3CaO.2SiO_2.3H_2O$) in veins which ramify and isolate cores of the more highly refracting disilicate.

This ready production of afwillite at the expense of tricalcium disilicate in nature is of interest in view of laboratory studies on the hydrothermal alteration of this compound. Flint, McMurdie, and Wells[1] treated the anhydrous silicate with water under pressure at elevated temperatures but failed to produce afwillite. The X-ray pattern of the alteration products so obtained could not be identified, but at the highest temperatures (500° C., 380 atmospheres) they obtained a new phase, which they identify as a low-temperature form of the tricalcium disilicate which on ignition is converted back to the usual form.

The second development of tricalcium disilicate is associated with certain flint nodules found in the metasomatized chalk. An account of these interesting assemblages has been detailed in earlier papers (Min. Mag., 1931, vol. 22, p. 443; 1934, vol. 23, p. 513; 1937, vol. 24, p. 569). The flint nodules pass by metasomatism into quartz-wollastonite aggregates encased by larnite-spurrite assemblages and the borders of the nodules are frequently rimmed by wollastonite crystals. The border of the nodule against the larnite-rock has frequently been the seat of later solutions which have attacked preferentially the less stable larnite, so that the immediate contact with wollastonite is represented by a narrow zone of alteration products. This zone affected by altera-

[1] Journ. Research Nat. Bur. Standards (Washington), 1938, vol. 21, pp. 628–629 [M.A. 7–283.]

tion may amount to less than a tenth of a millimetre in width and had previously been taken as representing altered larnite. Since that time a large number of sections across the critical border has revealed a number with perfectly fresh contacts and the photograph of pl. V, fig. 3, presents the relations then obtaining. The wollastonite crystals studding the border of the flint nodule are separated from the larnite aggregate by a very narrow zone of colourless crystals of lower refringence, birefringence, and the properties of which agree with those of $3CaO.2SiO_2$.

In one example these crystals extend in a small pocket into the larnite-rock forming a nest composed of wollastonite and $3CaO.2SiO_2$. The optical data on these crystals are as follows: optically positive, 2V 63°, α 1·640, β 1·644, γ 1·650, and these crystals exhibit the same feature of the slag compound in the absence of cleavage. Here, as in the border zone, wollastonite is always armoured from larnite by an intervening zone of the disilicate (pl. V, fig. 2).

The relations now described show a remarkable similarity to those developed in limestone fragments recrystallized in glass from the Kinghorn bottle works, Fife. In these G. V. Wilson noted the occurrence of $3CaO.2SiO_2$ together with wollastonite and melilite. An analysis of such material is quoted in table I, no. 2, and shows a close accordance with the Carnforth slag, composed essentially of the same minerals (pseudowollastonite in place of wollastonite).

Sections through some of these limestone xenoliths, cut from material presented by Mr. Wilson, have revealed that larnite is also developed among the other constituents noted above. Within the xenolith the phases $3CaO.2SiO_2$, melilite, and wollastonite occur as immediate associates, but where larnite is developed it is shielded from wollastonite by a zone of the disilicate. This feature is well shown in the photograph of pl. V, fig. 4, where a narrow rim to the larnite aggregate is built up of crystals of $3CaO.2SiO_2$, which in turn make contact with wollastonite concentrated at the edge of the enclosing glass.

For the new mineral the name rankinite is now proposed in honour of Mr. G. A. Rankin who has contributed so much to our knowledge of the binary and ternary systems in which it was first discovered as a constituent phase. Rankinite has closely similar refractive indices to the magnesium end-member of the monticellite series from which it may be distinguished by its moderate optic axial angle and lack of cleavage: from the iron-bearing monticellites it differs by its lower refraction and positive sign. In slags, monticellite is commonly elongated

parallel to the *a*-axis (elongation positive), while euhedral rankinite in the described slags exhibits negative elongation and inclined extinction.

The two 3-phase assemblages, rankinite–wollastonite–melilite and rankinite–larnite–melilite, are characteristic of the highest temperatures of metamorphism, for, with the exception that the wollastonite phase is represented by the higher-temperature form pseudowollastonite, they

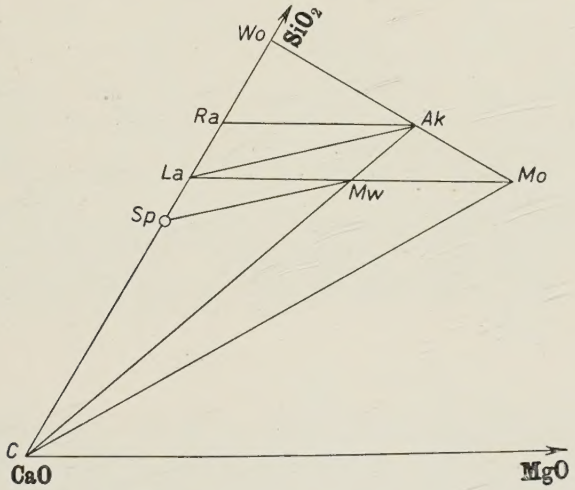

FIG. 1. Assemblages of the system CaO–MgO–SiO_2 in the Scawt Hill contact zone: Wo (wollastonite), Ak (åkermanite = melilite), Ra (rankinite), La (larnite), Mw (merwinite), Mo (monticellite). Spurrite (Sp) and calcite (C) are also indicated in projection, CO_2 being at the fourth corner of the tetrahedron.

form the equilibrium assemblages of the dry-melt systems CaO–Al_2O_3–SiO_2 and CaO–MgO–SiO_2 in which the melilite phase is represented by gehlenite and åkermanite respectively. The Scawt Hill assemblages corresponding to the latter system are represented in text-fig. 1.

Explanation of Plate V.

(All figures × 20 diameters.)

Fig. 1. Pseudowollastonite-melilite-rankinite slag, Carnforth, Lancashire.

Rankinite (equidimensional and elongated sections), pseudowollastonite (turbid feathery laths), with melilite partly enclosing the former.

Fig. 2. Rankinite-wollastonite-rock, Scawt Hill, Co. Antrim.

Rankinite forms the clear rounded grains and is intergrown with wollastonite, the latter especially prominent at the bottom and right of the photograph. In the upper part, darker grains of larnite surrounded by rankinite.

Fig. 3. Border of metasomatized flint nodule and larnite-rock, Scawt Hill, Co. Antrim.

The border of the flint nodule divides the photograph. The inner border is studded with wollastonite crystals which are separated from the encasing larnite-rock by a zone of rankinite crystals.

Fig. 4. Reconstituted limestone 'xenolith' in wollastonite-bearing glass, Kinghorn bottle works, Fife.

Wollastonite crystals in glass (above) are separated from the larnite (dark) by a rim of rankinite crystals. Left, aggregates of rankinite intergrown with melilite.

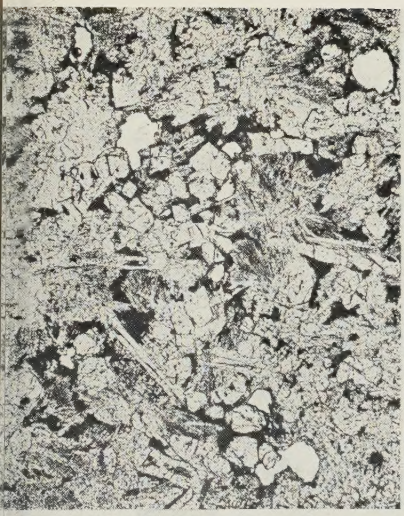

Fig. 1

Fig. 2

Fig. 3

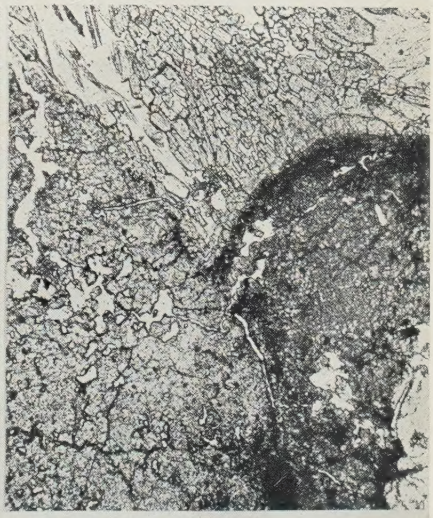

Fig. 4

C. E. Tilley: Rankinite.